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THEORETICAL DETERMINATION OF CONVECTION HEAT-TRANSFER COEFFICIENTS AROUND A TURBINE AIRFOIL (WITH COMPUTER PROGRAM)

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TECHNICAL REPORT AFAPL-TR-68-143

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This report describes a theoretical prediction of the convection heat-transfer coefficient distribution on a test blade and the computer program for making the necessary calculations. The program is written in Fortran IV ready for an IBM 7094. The input and output are described. The program starts with the blade surface pressure distribution obtained experimentally and yields the heat-transfer coefficients on the blade contour.

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FOREWORD

The work on which this report is based was accomplished under Project 3066, "Gas Turbine Technology," Task 306606, "Turbine Research Exploratory Development," using the computer facilities of the Turbine Engine Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. This work was administered under the direction of Mr. Charles E. Bentz, Project Engineer.

This report describes work conducted between 1 July 1968 and 1 October 1968. Mr. Walker Mitchell was responsible for the development of the computer program and Mr. Lucien Debruge for the theoretical development and discussion. This report was submitted by the authors October 1968.

This technical report has been reviewed and is approved.

Ernest C. Simpson

ERNEST C. SIMPSON
Director, Turbine Engine Division
Air Force Aero Propulsion Laboratory

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ILLUSTRATIONS

SYMBOLS

A	channel cross-sectional area
A^*	channel cross-sectional area at which Mach number is unity
C_f	turbulent coefficient of skin friction
C_p	specific heat at constant pressure
h	convection heat-transfer coefficient
H	velocity shape factor (turbulent boundary layer)
n	distance along velocity potential line
N_x	local Nusselt number
P	pressure
P_r	Prandtl number
r	radius
R	gas constant
T	temperature
V or U	velocity
V_{my}	mid channel reference velocity at a distance my from centerline of cascade
x	surface distance from stagnation point
y	distance along radial potential line
ρ	density
γ	ratio of specific heats
ν	kinematic viscosity
μ	viscosity
δ	boundary layer thickness
δ^*	displacement thickness
δ^{**}	boundary layer energy thickness
λ	velocity shape factor (laminar boundary layer)
θ	momentum thickness
τ	shearing stress

SUBSCRIPTS

m	refers to mid-channel conditions
CR	refers to critical condition
o	stage entrance conditions (cold flow)
1	stage entrance conditions (hot flow)
n	distance along velocity potential line
no	distance along potential line (cold flow)
nl	distance along potential line (hot flow)
S	static conditions
ad	adiabatic conditions

SECTION I

INTRODUCTION

Currently, the Air Force Aero Propulsion Laboratory is installing an in-house High-Temperature Test Facility which will be used initially to analyze various cooling techniques, as applied to turbine engine blades, over an extended gas temperature range. The objective is to evaluate these cooling schemes with respect to gas temperature and pressure levels. Experimental data will be correlated with the various theoretical predictions of blade cooling effectiveness, thus providing a basis for future high-temperature turbine blade designs

The experimental data used is that obtained from the recording of surface metal temperatures by infrared thermometry. In the theoretical prediction of turbine blade temperatures, cooled or uncooled, the major steps are the calculation of the convection heat-transfer coefficients on the blade surface and the calculation of the driving or adiabatic wall temperatures. These calculations depend primarily on the accuracy with which the behavior of the boundary layer is predicted. It is generally assumed that the introduction of a cooling fluid in the boundary layer has a negligible effect on the convection heat-transfer coefficients, but it affects considerably the adiabatic or driving wall temperature.

This report presents a theoretical approach to the problem of determining the adiabatic wall temperatures and the convection heat-transfer coefficients .

This program is written in Fortran IV ready for use on an IBM 7094 for an uncooled blade and the computer program to which it led. The results obtained from the program developed here are compared with those from the computer program developed by the Allison Division of General Motors on Contract AF 33(615)-2985.

SECTION II

THEORY AND DISCUSSION

The velocity of a perfect, frictionless, compressible gas flowing through a channel, at any point across a potential line, is given by the equation

$$V = V_{my} \exp\left[-\frac{n}{2\Delta C}\left(C^2 - C_m^2\right)\right] \qquad (1)$$

where, for a nonrotating channel,

$$V_{my} = V_{yo} \exp\left[\int_{yo}^{y} -\frac{1}{r} \sin^2\phi \, dy\right] \qquad (2)$$

is the mid channel velocity at a distance y from a reference point y_o along a radial potential line and V_{yo} is the velocity at the reference point (Figure 1). It is seen from Equations 1 and 2 that V is strictly a function of channel geometry and V_{yo}.

In the computer program currently in use at AFAPL (Reference 1), V_{yo} is arbitrarily chosen; then, the fluid velocity and density are evaluated at specified locations along a velocity potential line, the latter being obtained from the equation

$$\rho_n = \rho_1 \left\{1 - \left(\frac{\gamma - 1}{\gamma_1 + 1}\right)\left(\frac{V_n}{V_{CR}}\right)^2\right\}^{\left(\frac{1}{\gamma_1 - 1}\right)} \qquad (3)$$

Integration of the product $V_n \rho_n$ over a given channel cross section yields the total mass flow which is compared with the required flow (usually the maximum or choked flow). V_{yo} is improved until $\int_A \rho_n V_n \, dA$ (required flow) $\leq$ tolerance. Use of this computer program requires an accurate description of the channel configuration at each of the cross sections where the channel wall velocity must be obtained. Eleven cross sections are presently used to provide enough data for interpolation of the velocity profile along the channel walls between the stage entrance and the throat, beyond which extrapolation is depended upon to obtain the velocity profile. As inputs to the program, curvatures, length of velocity potential lines, and the angle between the gas stream direction upstream of stage entrance and the mid channel stream-line must be measured or calculated. A table of V/V_{cr} versus axial chord

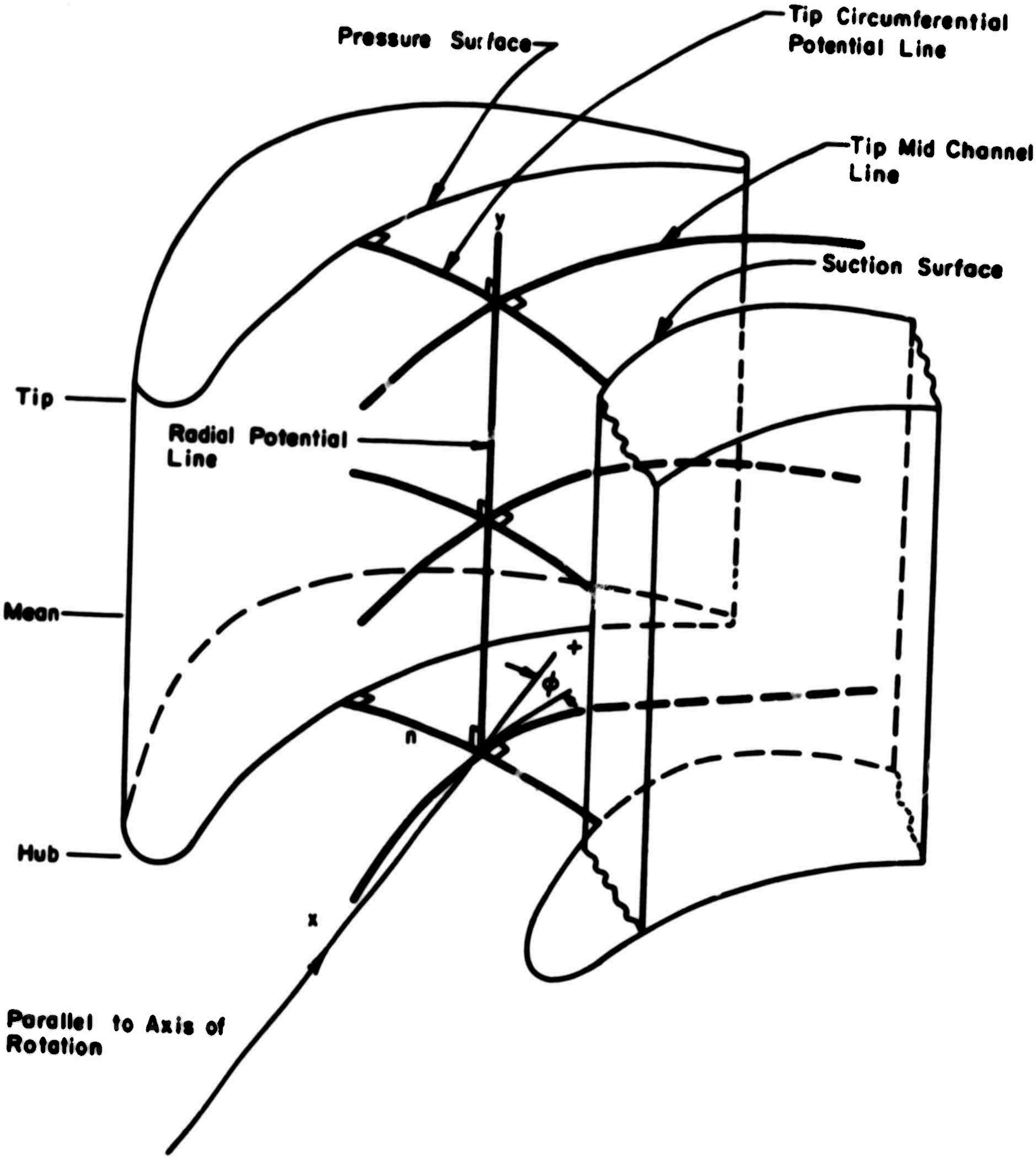

Figure 1. Channel Configuration (From Reference 1)

distance must be prepared from a curve drawn through the extrapolated and interpolated points as an input to a second program (described later) which in turn translates V/V_{CR} versus axial chord distance into V/V_{CR} versus surface distance from the blade stagnation point and ultimately yields the convection heat-transfer coefficients along the blade profile.

It follows that, even when only changes in the gas flow parameters (P_0, T_0, R_0, γ_0, V_0) are involved, preparation of a new table from the output of the first computer program requires several hours. When a different blade profile must be tested, a tedious, time-consuming determination of the channel parameters listed above must also be conducted.

A method is herein described which uses solely as inputs the static pressure distribution on the blade surface, obtained directly from the cold flow test described in Reference 2, and the gas flow parameters at the stage entrance for both the cold flow and hot flow tests. This method proceeds as follows:

Maximum flow per unit area (cold flow):

$$\frac{W_0}{A^*} = P_0 \left[\frac{g\ \gamma_0}{R_0\ T_0}\right]^{\frac{1}{2}} \left[\frac{2}{\gamma_0 + 1}\right]^{\frac{(\gamma_0 + 1)}{2(\gamma_0 - 1)}}$$

Maximum flow per unit area (hot flow): (4)

$$\frac{W_1}{A^*} = P_1 \left[\frac{g\ \gamma_1}{R_1\ T_1}\right]^{\frac{1}{2}} \left[\frac{2}{\gamma_1 + 1}\right]^{\frac{(\gamma_1 + 1)}{2(\gamma_1 - 1)}}$$

Fractional change in flow rate:

$$FR = \frac{W_1 - W_0}{A^*} \tag{5}$$

Densities (inlet conditions):

$$\rho_0 = P_0 / R_0 T_0 \ ; \ \rho_1 = P_1 / R_1 T_1$$

Critical velocities:

$$\begin{aligned} V_{CRO} &= \left[2\ R_0\ g\ \ (\gamma_0/\gamma_0 + 1)\ T_0\right]^{\frac{1}{2}} \\ V_{CR1} &= \left[2\ R_1\ g\ \ (\gamma_1/\gamma_1 + 1)\ T_1\right]^{\frac{1}{2}} \end{aligned} \tag{6}$$

Local channel cold flow densities:

$$\rho_n = \rho_o \left[1 - \left(\frac{\gamma_o - 1}{\gamma_o + 1}\right)\left(\frac{V_{no}}{V_{CRO}}\right)^2\right]^{\frac{1}{\gamma_o - 1}} \tag{7}$$

Desired local channel, hot-gas mass flow:

$$\rho_{no} \; V_{no} + \left(\rho_{no} \; V_{no}\right)\left(FR\right) = GO \tag{8}$$

Local channel hot flow density:

$$\rho_{n1} = \rho_1 \left[1 - \left(\frac{\gamma_1 - 1}{\gamma_1 + 1}\right)\left(\frac{V_{no} + \Delta V_{no}}{V_{CR_1}}\right)^2\right]^{\frac{1}{\gamma_1 - 1}} \tag{9}$$

ΔV_{no} is changed until

$$GO - \rho_{n1} \left(V_{no} + \Delta V_{no}\right) \leq \text{tolerance}$$

Figures 2 and 3 show the velocity versus axial chord distance plots obtained from the former computer program and the present method for identical input gas stream conditions.

The computer program presently in use at AFAPL calculates convection heat-transfer coefficients and adiabatic wall temperatures along the blade profile. Static temperature and pressure are calculated outside the boundary layer from channel flow theory, using the following equations:

$$T_S = T_o \left[1 - \left(\frac{\gamma - 1.}{\gamma + 1.}\right)\left(\frac{U(x)}{U_{CR}}\right)^2 \right]$$

$$P_S = P_o \left(\frac{T_S}{T_o}\right)^{\frac{\gamma}{\gamma - 1}}$$

C_P , μ , P_R, and ρ , characteristic of the fluid, are entered as tables for the appropriate range of temperatures and pressures.

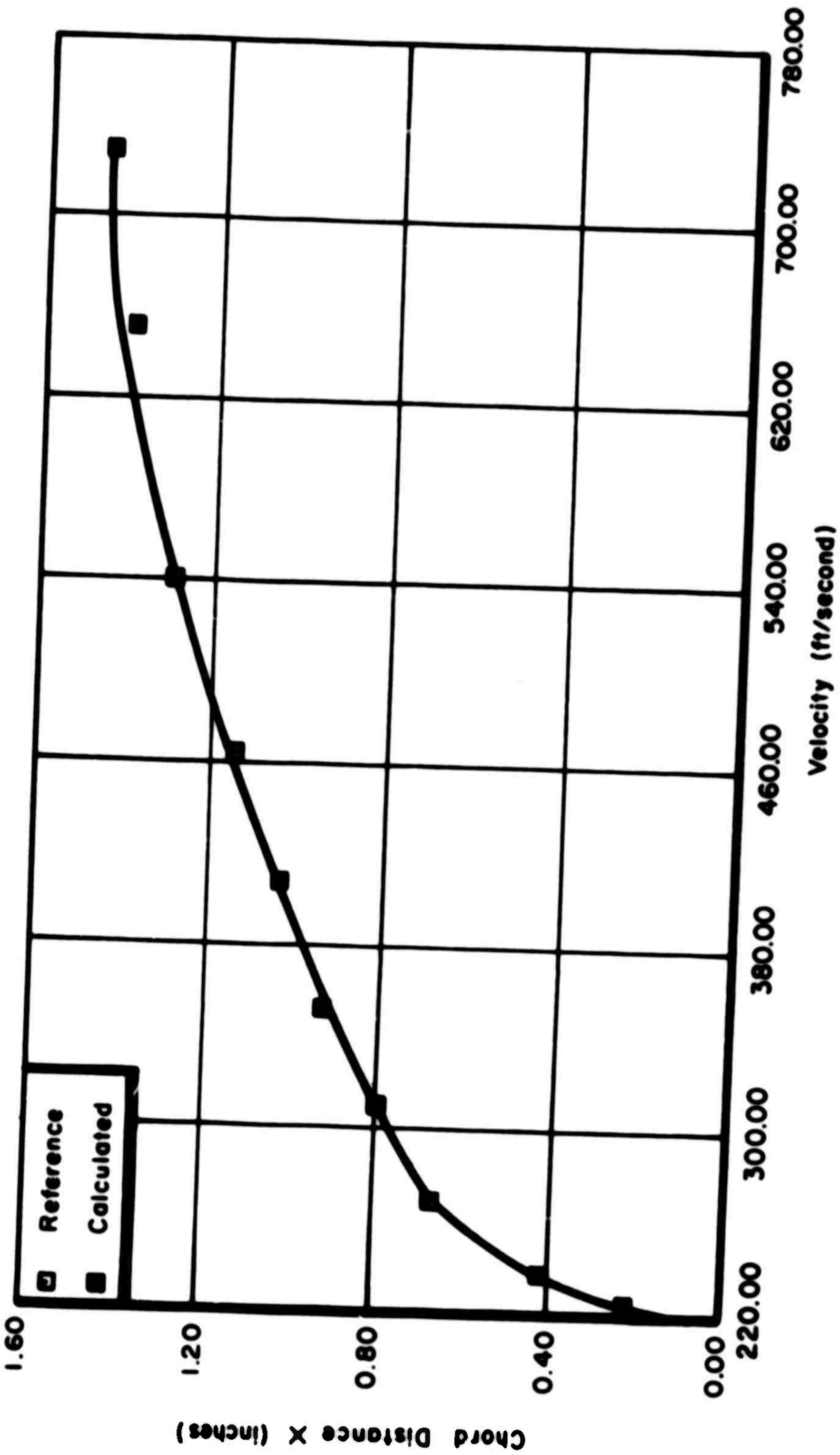

Figure 2. Suction Surface Velocity

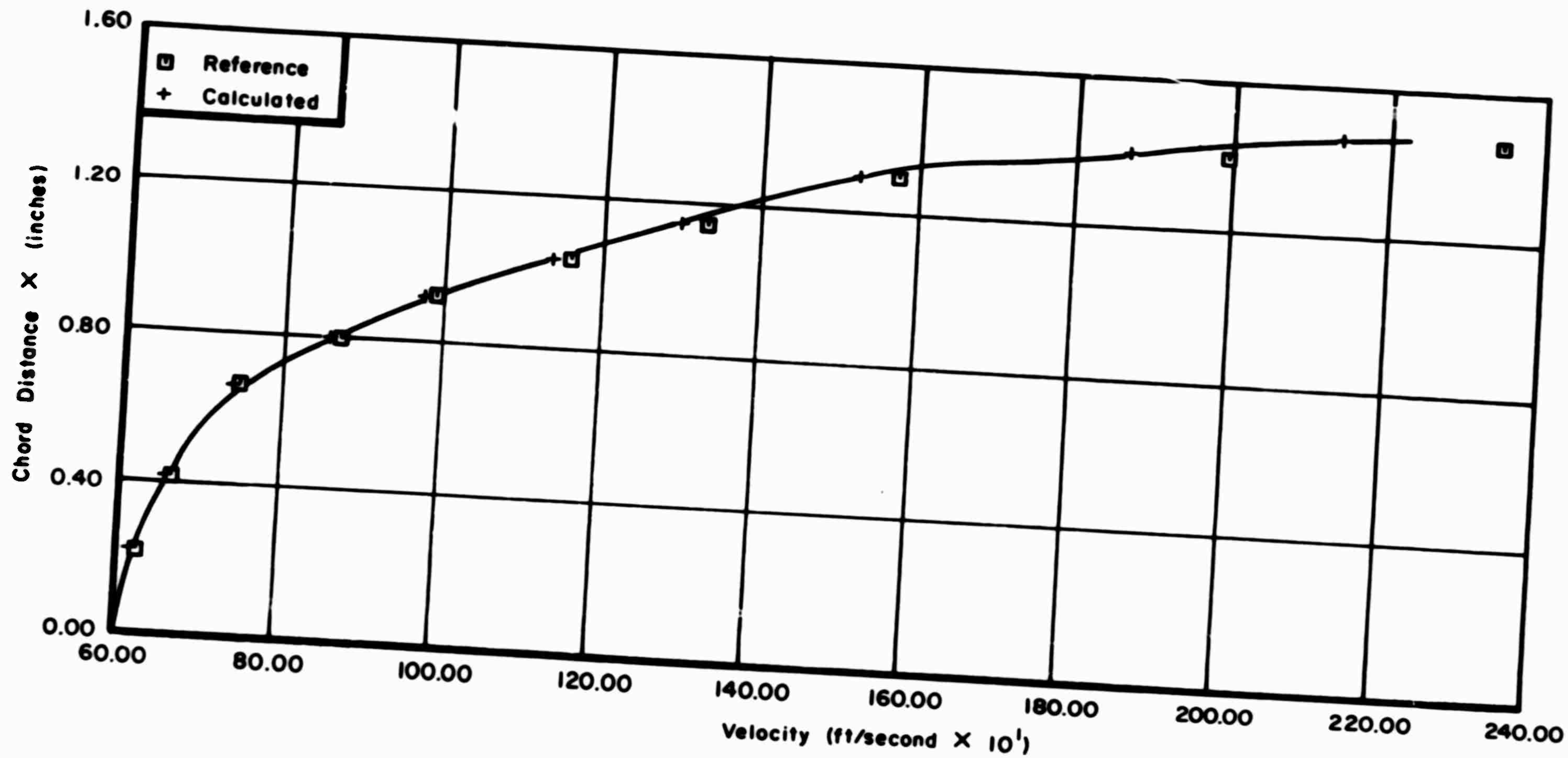

Figure 3. Pressure Surface Velocity

The calculation of convection heat-transfer coefficients and adiabatic wall temperatures is then carried out on the following assumptions:

1. On the suction side, the boundary layer is laminar from the stagnation point to the point of minimum pressure. From this latter point on, the flow is turbulent.

2. On the pressure side, the boundary layer is turbulent from the neighborhood of the stagnation point to the trailing edge.

The adiabatic wall temperatures are obtained from the following equations:

$$\text{(laminar)} \qquad T_{ad} = T_S + (T_o - T_S)\, P_R^{\frac{1}{2}}$$

$$\text{(turbulent)} \qquad T_{ad} = T_S + (T_o - T_S)\, P_R^{\frac{1}{3}}$$

On the leading edge and in the laminar part of the boundary layer, Squire's method (Reference 3) for the calculation of heat transfer on a cylinder and on a flat plate is used. In the turbulent part of the boundary layer, an approximation of the von Karman formula for heat transfer in turbulent flows is used.

$$N_x = \frac{1}{2} C_f' \, P_R^{\frac{1}{3}} \, R_x$$

assuming the local coefficient of skin friction for a flat plate to be

$$\frac{1}{2} C_f' = \frac{\tau_o}{\rho U^2} = 0.0128 \left(\frac{U\theta}{\nu}\right)^{-\frac{1}{4}} \qquad (10)$$

where

$$\theta_{(x)} = 0.036\, x \left(\frac{Ux}{\nu}\right)^{-\frac{1}{5}} \qquad (11)$$

The fact that the Reynolds numbers anticipated in the testing of the blades will be low, $\approx 10^5$, and that, for the pressure profiles obtained (Figure 4), $\frac{dP}{dx}$ is small in an extended neighborhood of the minimum pressure point makes questionable the assumption that the latter coincides with the transition point. Also, Equation 11 suggests that $\theta(x)$ is rather insensitive to fluctuations in U, the latter being overshadowed by those in x. A comparison of Figures 4 through 6 shows that the drastic changes in the velocity profiles, particularly on the pressure side, are not reflected in $\theta(x)$ and that, for instance, the momentum thickness of the turbulent boundary layer is approximately the same on both pressure and suction surfaces beyond a surface distance of 1.3 inch, corresponding approximately to the transition point on the suction side. Obviously, this behavior of θ will

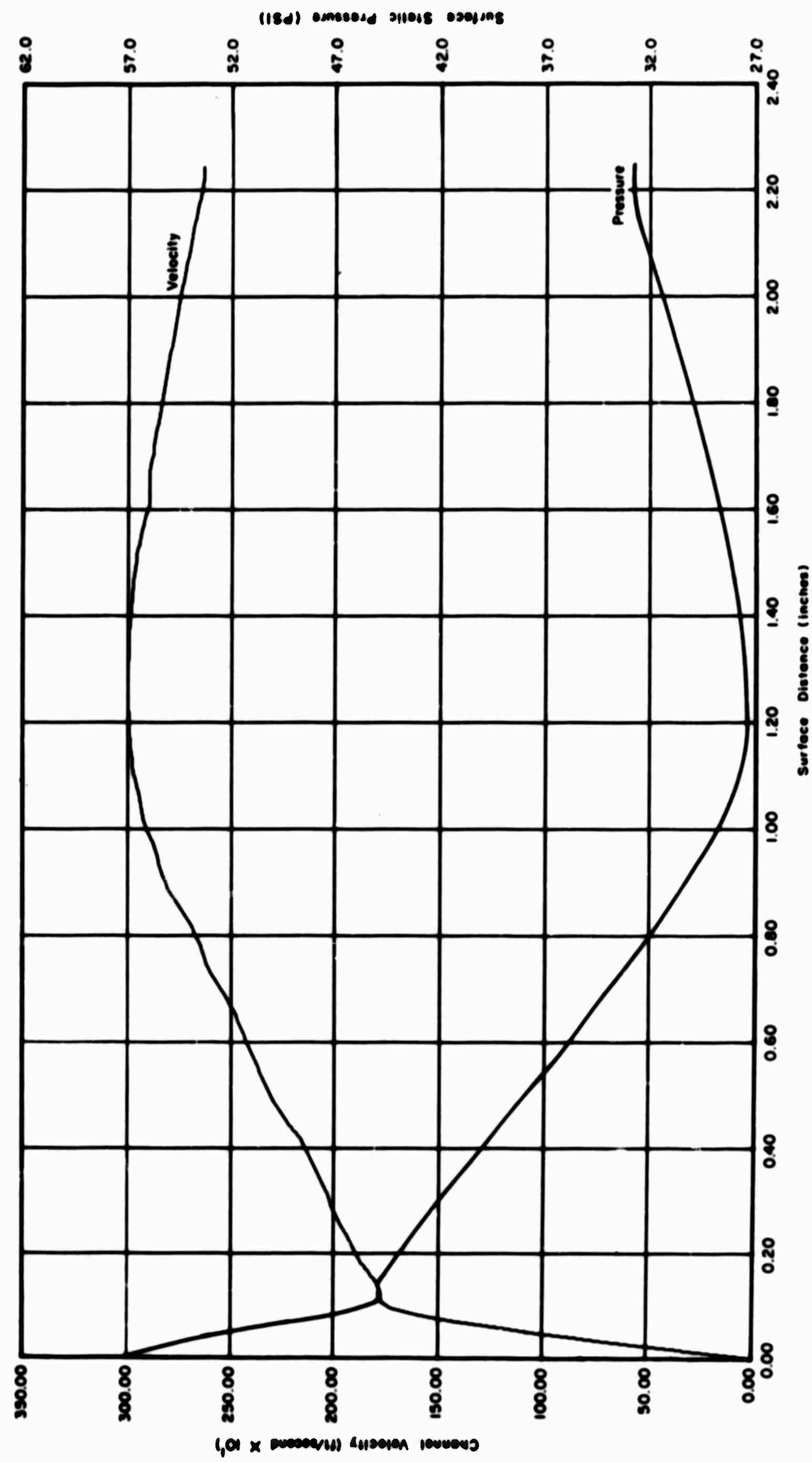

Figure 4. Suction Surface Velocity and Pressure

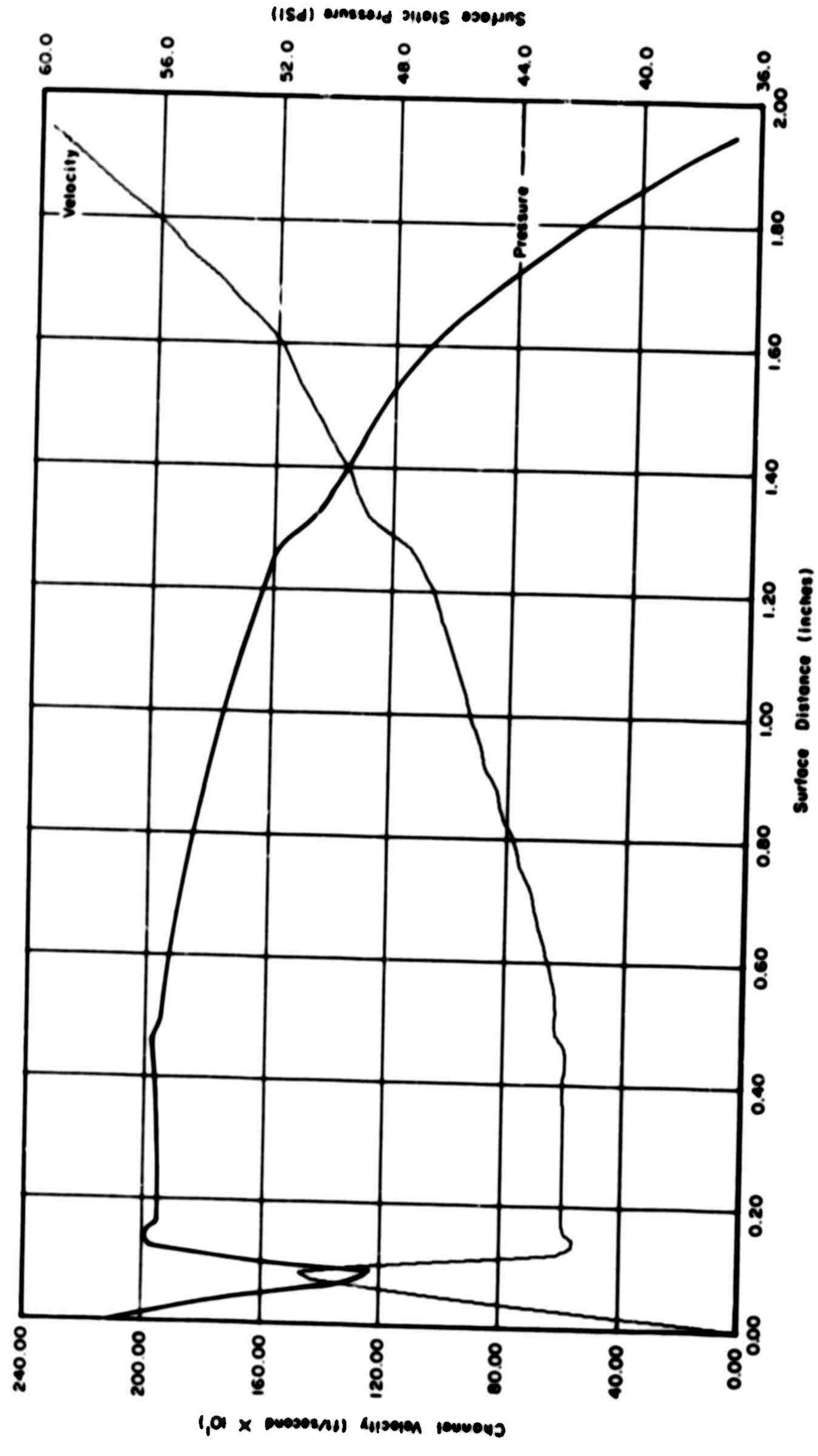

Figure 5. Pressure Surface Velocity and Pressure

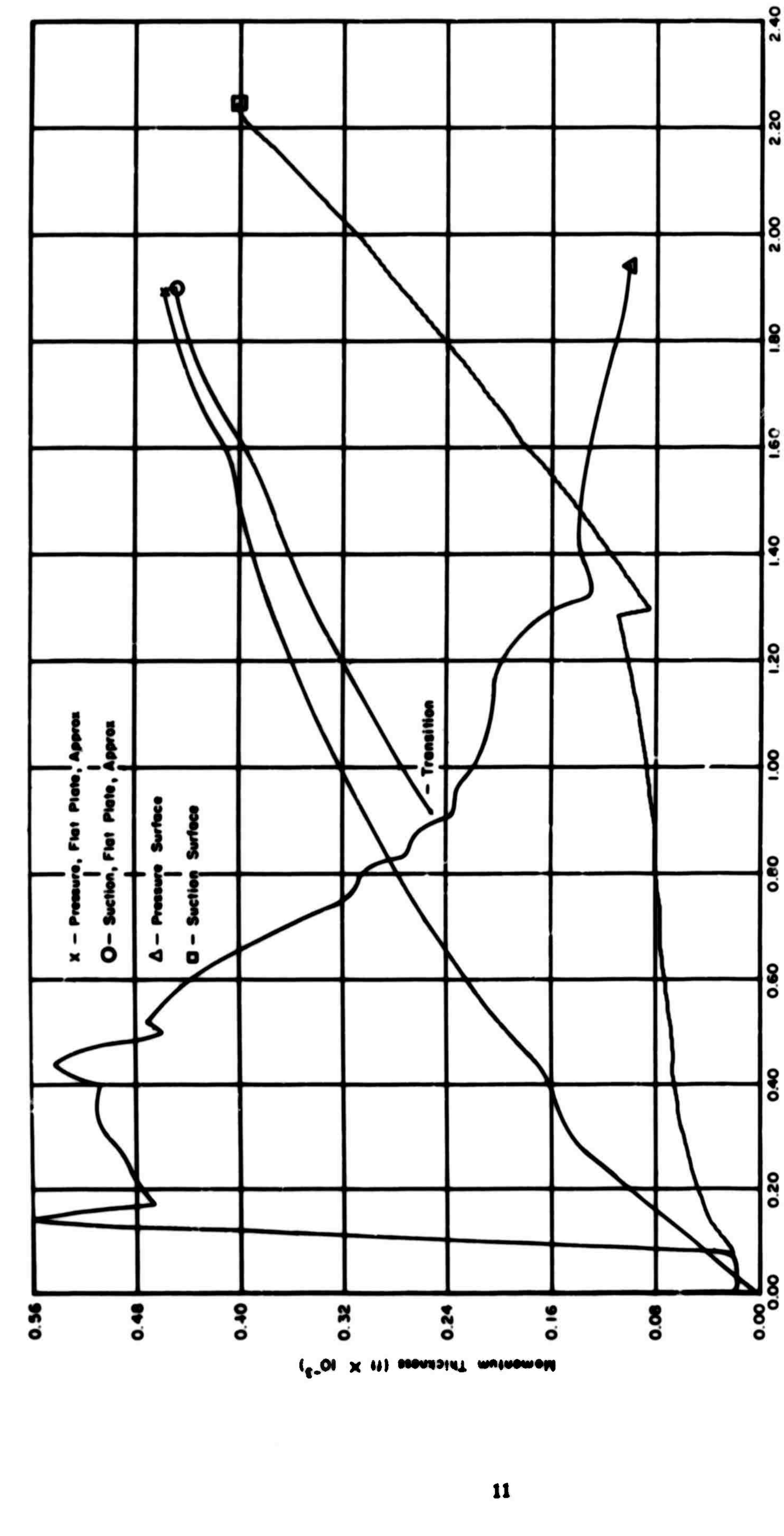

Figure 6. Momentum Thickness

be reflected in N_x, since

$$N_x \text{ varies with } \theta^{-\frac{1}{4}}, \text{ and, therefore, } h(x)$$

In an attempt to evaluate the discrepancies that might result from the preceding observations, we have adopted the theories of H. Schlichting and E. Truckenbrodt (References 4 and 5, respectively) relative to the determination of the transition point and to the computation of a two-dimensional turbulent boundary layer momentum thickness, to the specific requirements of AFAPL turbine blade hot testing investigation and incorporated them in a computer program described in this report. These theories will be described briefly.

In the new program, the laminar boundary layer is calculated using Squire's method which uses a simple quadrature to obtain θ, where

$$\theta^2 = \frac{0.47\nu}{U^6}\int_{x=0}^{x} U^5\,dx \tag{12}$$

The displacement thickness δ^* and boundary layer thickness δ are obtained from the assumptions

$$\frac{\delta}{\theta} = \frac{315}{37}\ ;\ \frac{\delta^*}{\delta} = \frac{3}{10}$$

The shape factor of the boundary layer velocity profiles is defined as

$$\lambda = \frac{\delta^2}{\nu}\,\frac{dU}{dx}$$

The pressure decreases for $\lambda > 0$ and increases for $\lambda < 0$, hence the point of minimum pressure occurs for $\lambda = 0$

Original form:

$$\frac{\delta^*}{\delta} = \frac{3}{10} - \frac{1}{120}\lambda\ ;\ \frac{\theta}{\delta} = \left(\frac{37}{315} - \frac{1}{945}\lambda - \frac{1}{9072}\lambda^2\right)$$

A family of neutral stability curves defined by the shape factor λ and representing the variation of δ^* with the Reynolds number $\frac{U\delta^*}{\nu}$ has been obtained by H. Schlichting and A. Ulrich (Reference 4). The point on these curves at which the Reynolds number R_{δ^*} has its smallest value is defined as the limit of stability for the laminar flow of interest. This R_{δ^*} is called the critical Reynolds number, $R_{\delta^*_{CR}}$.

It follows that R_{δ^*CR} can be plotted as a function of λ , hence, of the surface distance x. The intercept of this curve with that representing the variation of the local Reynolds number $\frac{U\delta^*}{\nu}$ with x will yield the separation point.

As may be seen from Figures 7 and 8 for small x's, R_{δ^*} is small and λ is large. As x becomes larger, this relationship is inverted and consequently R_{δ^*CR} decreases while R_{δ^*} increases.

The tormented profile of the variation of R_{δ^*} with x is to be attributed to the dependence of λ on $\frac{dU}{dx}$ which undergoes abrupt changes along the blade surface.

The calculation of θ from E. Truckenbrodt's method (Reference 5) is based on the energy integral equation

$$\frac{1}{U^3}\frac{d}{d_x}\left(U^3\delta^{**}\right) = \frac{1.12 \times 10^{-2}}{\left(\frac{U\theta}{\nu}\right)^{\frac{1}{6}}} \tag{13}$$

where the energy thickness δ^{**} is a measure of the kinetic energy loss resulting from friction and is defined as

$$U^3\delta^{**} = \int_0^{\infty} U(y)\left[U^2(x) - U^2(y)\right] dy$$

and

$$\frac{1.12 \times 10^{-2}}{\left(\frac{U\theta}{\nu}\right)^{\frac{1}{6}}}$$

represents a good approximation of the friction work performed in the boundary layer by the shearing stresses τ (H. Schlichting).

Integration of Equation 13 was performed by E. Truckenbrodt (Reference 5) and yields

$$\theta\left(\frac{U\theta}{\nu}\right)^{\frac{1}{n}} = C_1 + A\int_{x=x_t}^{x}\frac{U^{3+2n}}{U^{3+\frac{2}{n}}}dx$$

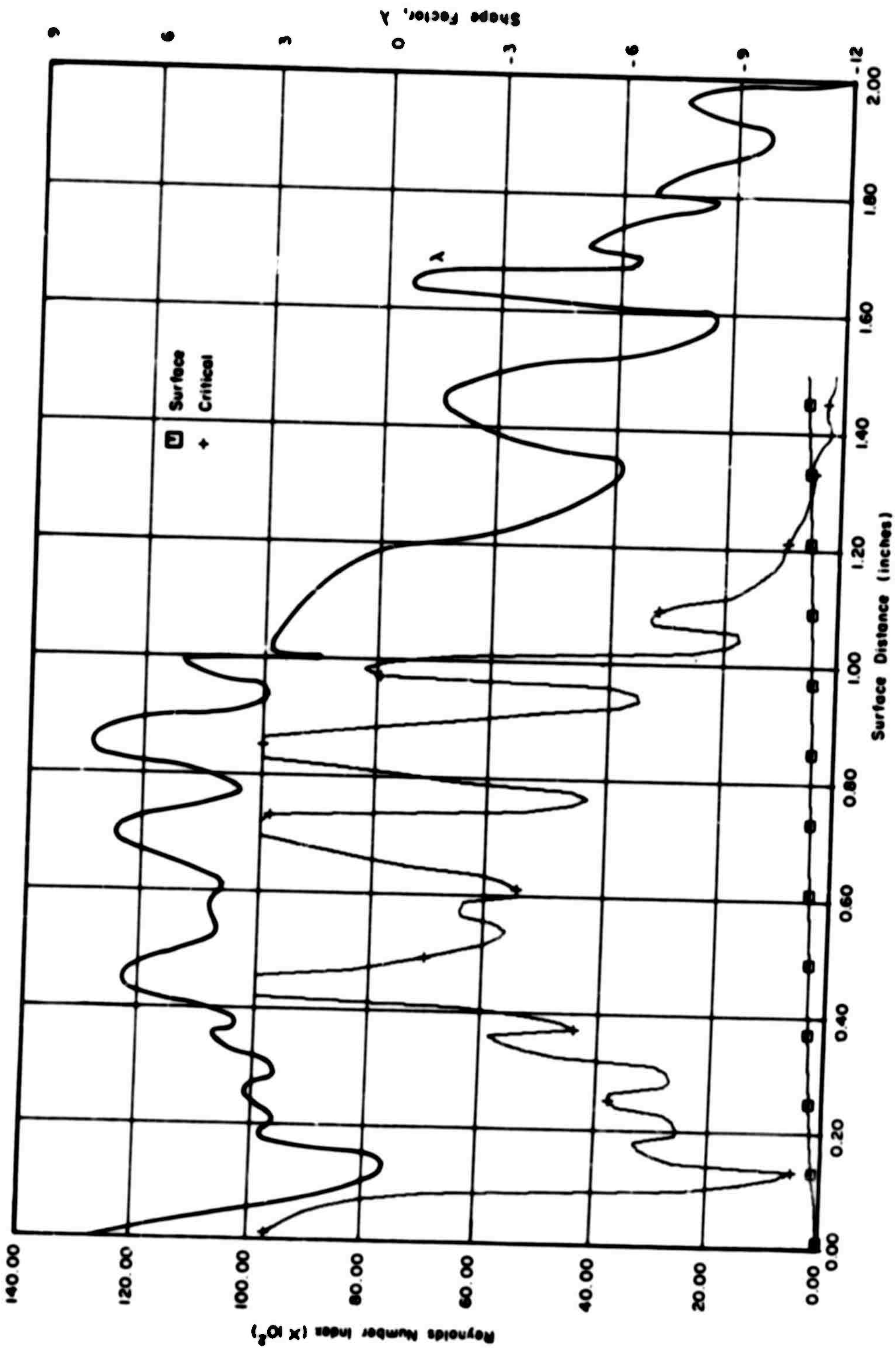

Figure 7. Suction Surface Reynolds Number

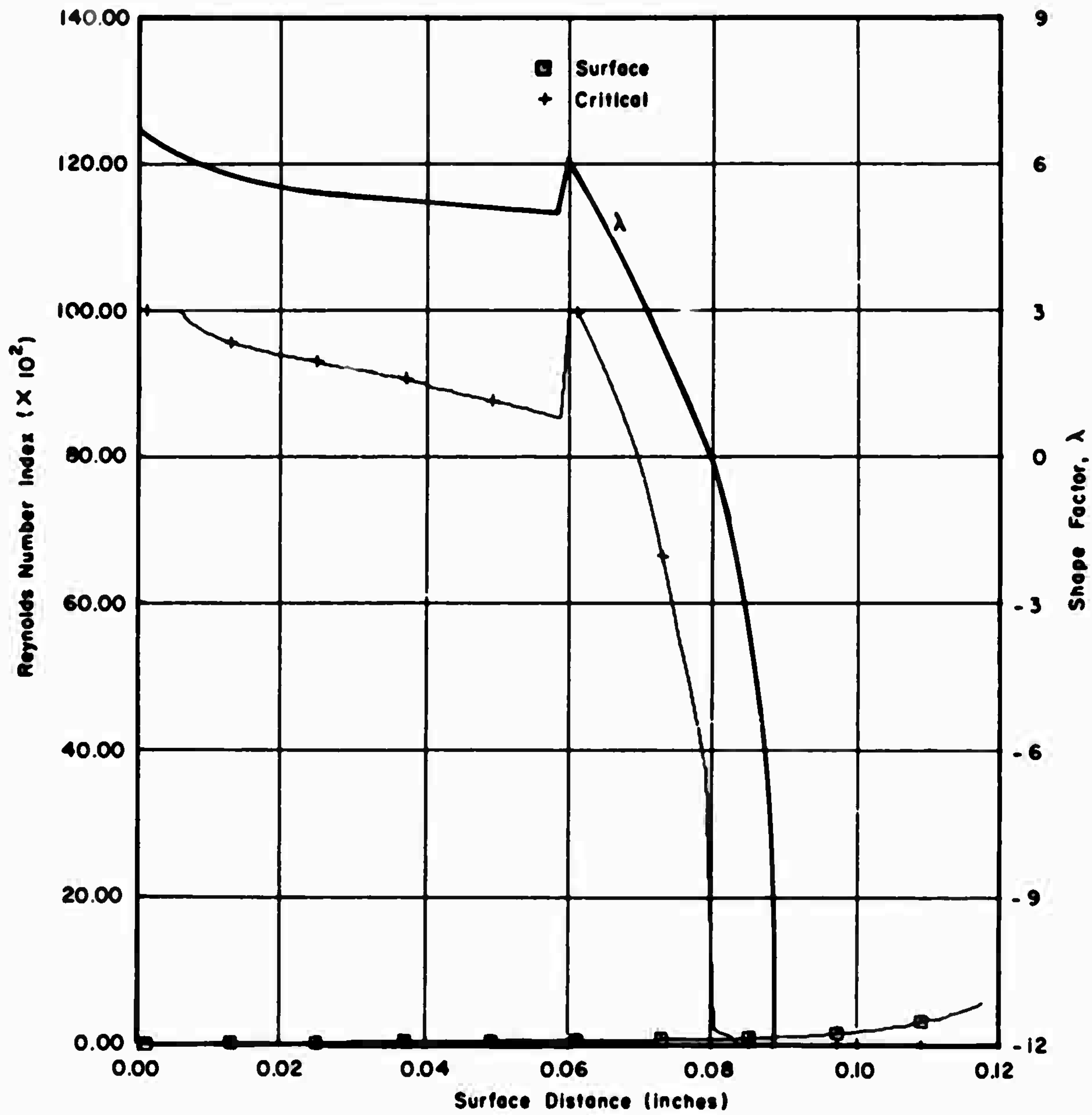

Figure 8. Pressure Surface Reynolds Number

which may be rewritten using the turbulent coefficient of skin friction for a flat plate as

$$\frac{\theta(x)}{\ell} = \left(\frac{U}{U_\infty}\right)^{-3}\left\{C_1^* + \left(\frac{C_f}{2}\right)^{\frac{n+1}{n}}\int_{\frac{x_t}{\ell}}^{\frac{x}{\ell}}\left(\frac{U}{U_\infty}\right)^{3+\frac{2}{n}} d\left(\frac{x}{\ell}\right)\right\}^{\frac{n}{1+n}} \qquad (14)$$

where

$$C_1^* = \left[\frac{1}{2} C_f \ell \left(\int_0^{\frac{x_t}{\ell}}\left(\frac{U}{U_\infty}\right)^5 d\left(\frac{x}{\ell}\right)\right)^{\frac{1}{2}}\right]^{\frac{(n+1)}{n}}$$

represents the laminar portion of the boundary layer.

It may be seen from Equation 14 that θ is highly sensitive to the variations in the velocity U. Figures 4 through 6 afford a comparison of the variations of θ and U with respect to x for the suction and pressure sides.

A very good value of the local coefficient of skin friction could have been obtained through the relationship

$$\frac{\tau_0}{\rho U^2} = .123 \times 10^{-.678 H}\left(\frac{U\theta}{\nu}\right)^{-.268}$$

but unfortunately E. Truckenbrodt's method for the variation of the shape factor H in the range of transition could not be used because $\frac{U\theta}{\nu}$ in this range was too small. Instead, $\frac{1}{2}C_f'$ was obtained from

$$\frac{\tau_0}{\rho U^2} = .0128\Big/\left(\frac{U\theta}{\nu}\right)^{.25}$$

and this value introduced into the von Karman formula

$$N_x = \frac{\frac{1}{2} C_f' \, R_x \, P_R}{1 + 5\sqrt{\frac{1}{2}C_f'}\left\{\left(P_r - 1\right) + \ln\left(1 + \frac{5}{6}\left(P_r - 1\right)\right)\right\}}$$

which takes into account the variation of the Prandtl number.

The convection heat-transfer coefficient for the laminar part of the boundary layer is calculated from Squire's method, using the universal function

$$H\left(\frac{\delta_T}{\delta}\right) = H(\Delta) = \frac{3}{10} - \frac{3}{10}\frac{1}{\Delta} + \frac{2}{15}\frac{1}{\Delta^2} - \frac{3}{140}\frac{1}{\Delta^4} + \frac{1}{180}\frac{1}{\Delta^5}$$

obtained from intergration of the energy equation with $P_r < 1$. Squire's paper (Reference 3) is referred to for the details of the procedure. The new computer program, instead of using a table of H versus Δ, computes $H(\Delta)$ at every point where h is calculated.

SECTION III

RESULTS AND CONCLUSIONS

On the suction side, the transition point as determined in the new program is shifted by 0.37 inch downstream. At this point h_T is 35% higher than the h obtained from the former program at the same location (Figure 9). On the pressure side, Figure 10 shows that the new convection heat-transfer coefficient assumes lower values immediately downstream of the transition point with a maximum change of 40% with respect to the former h at the same location and increases at a faster rate to assume a value at the trailing edge representing an increase of 36% over the former h.

The average value of h over the blade remains essentially unchanged when Truckenbrodt's method is used, so that the total amount of coolant required for the blade will not be changed significantly.

The large discrepancies in local heat-transfer coefficients would necessitate a redistribution of the coolant flow formerly determined from the Allison program.

Confirmation of the validity of the improvements suggested in this report will necessitate experimental data which will become available when the AFAPL in-house testing program is initiated.

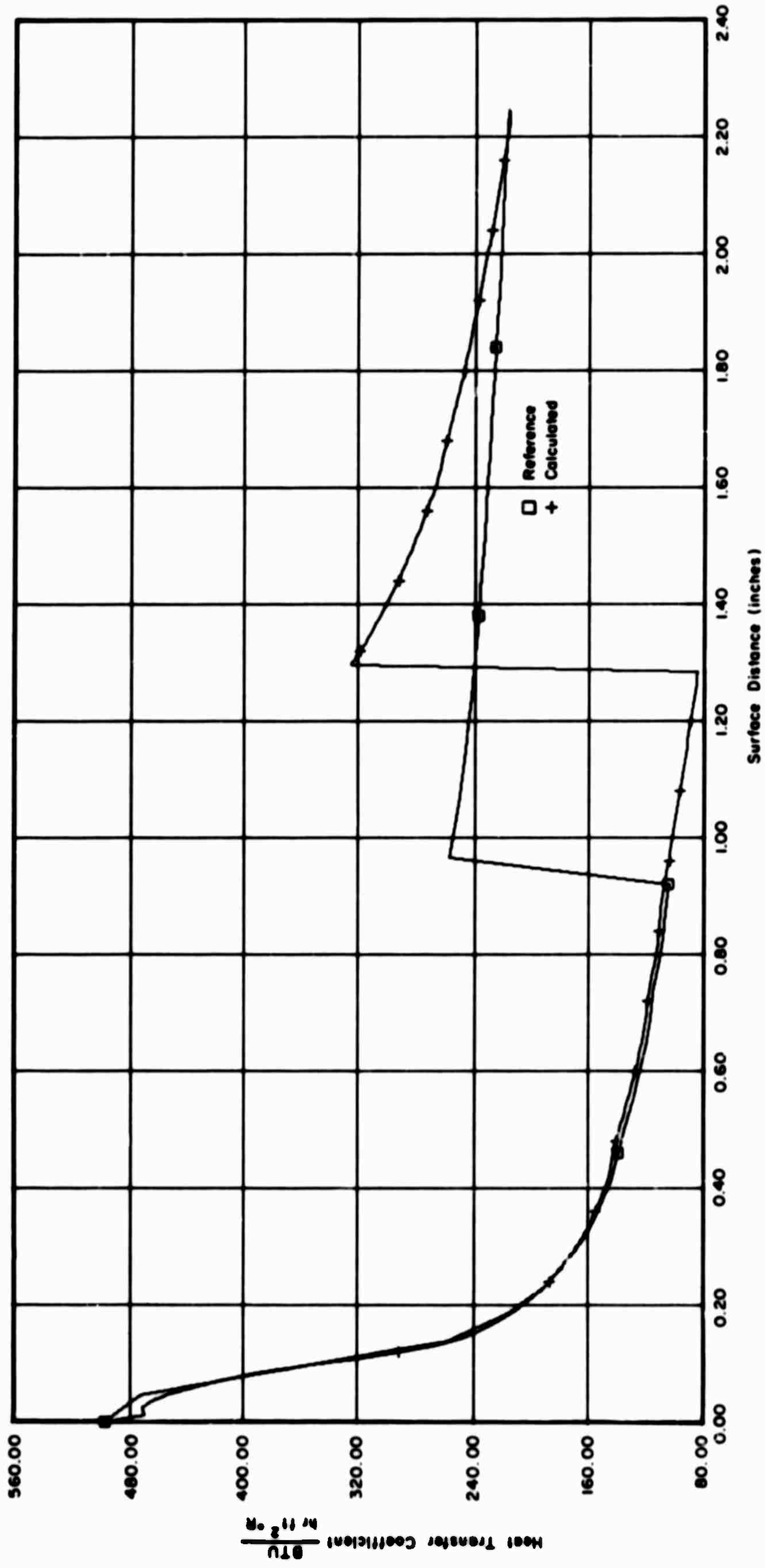

Figure 9. Suction Surface Heat-Transfer Coefficient

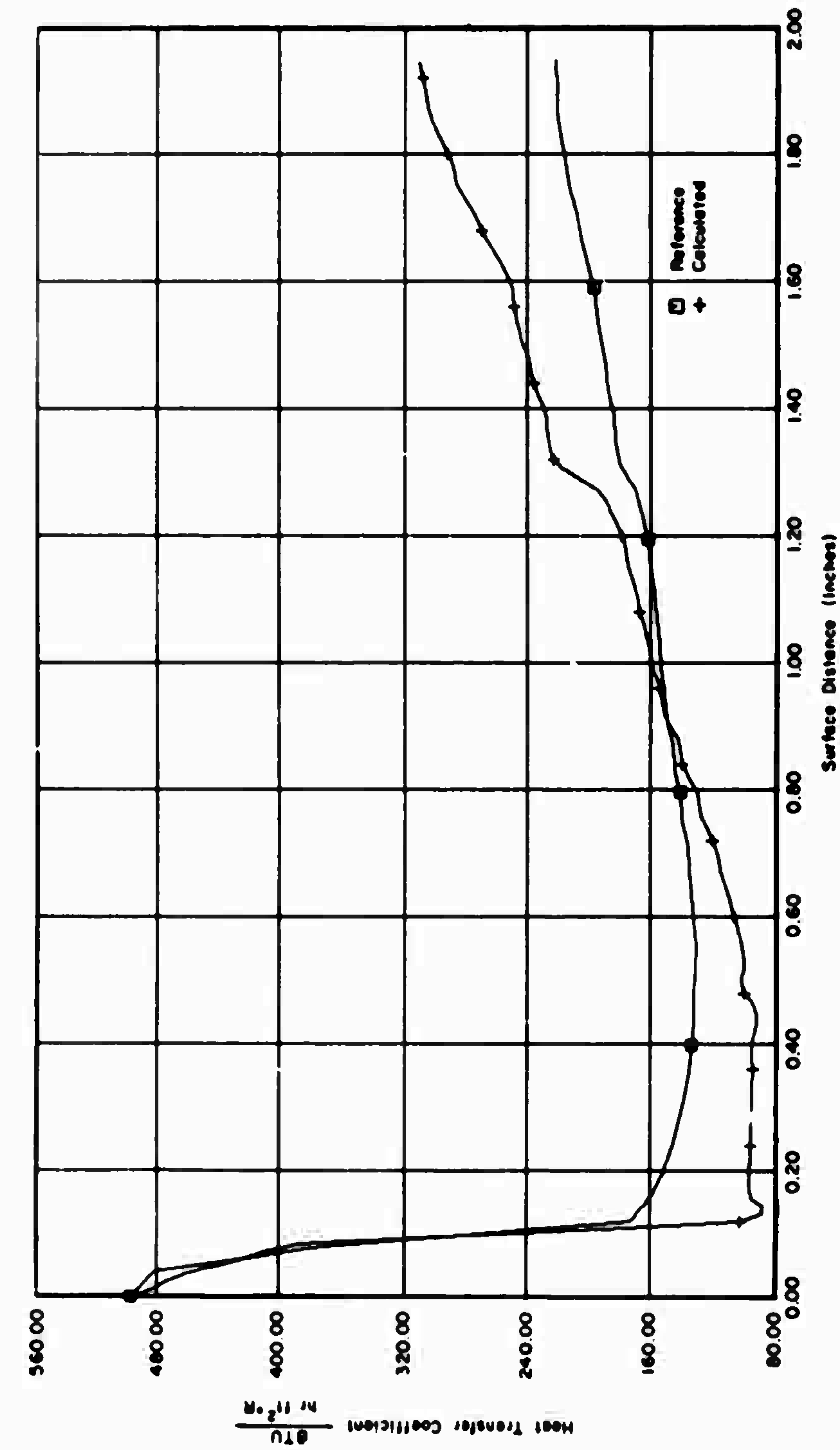

Figure 10. Pressure Surface Heat-Transfer Coefficient

APPENDIX

COMPUTER PROGRAM

PROGRAM FUNCTIONS

LUMIT

This is the main program. It is divided into two basic parts: laminar boundary layer and turbulent boundary layer. Initially the program reads in the input data, calculates the initial conditions of the laminar boundary layer, iterates through the laminar calculations until transition is reached, then proceeds into the turbulent section and iterates until the end of the blade is reached. All integrations are performed in the program and are basically trapezoidal.

VLOCT (alternate entry CURVE)

This routine reads in the velocity profile versus surface distance. It uses the alternate entry to find the velocity and the first and second derivatives for a given surface distance. It should be noted that the first and second derivatives are somewhat inaccurate since they are based upon a finite length rather than a point.

Uses subroutine TLOCK

DTFRMX

This routine solves the universal function of DELTA for DELTA greater than 1. It iteratively solves for the unknown DELTA given H (DELTA).

Uses subroutine AFQUIR.

See Chapter XII of Reference 3.

PRANX

This routine looks up in a table the constant used in the heat-transfer equation near the stagnation point as a function of the Prandtl number.

Uses subroutine SRCHX

PROPEX

This routine calculates the viscosity, density, Prandtl number, and specific heat of air as a function of temperature and pressure.

Uses subroutine PROCOM and TLOOK.

TLOOKX

The function subprogram TLOOK is a general purpose routine to perform a table look-up in a two-dimensional table (dependent variable versus independent variable). It first locates the input independent variable in its table, then takes the nearest 'N' pairs of points and calls subroutine LAGRNG. This program uses an interpolating polynominal of degree 'N-1', in the Lagrangian form, to evaluate the dependent variable. TLOOK also has the capability of remembering where it found the independent variable in the table. Thus, search time is saved when the next time it is called the independent variable has changed only slightly.

Use subroutine LAGRNG.

LAGRNG

See description of TLOOKX.

SRCHXX

This subprogram is a table lookup routine using linear interpolation.

PROCOM

This routine calculates the thermodynamic properties of air or air-JP4 mixtures. Given temperature and fuel-air ratio, it calculates speed of sound, ratio of specific heats, specific heat of constant pressure, gas constant, and nonpressure biased entropy and enthalpy.

AFQUIR

This program is a quadratic convergence routine. It is a routine having general application and is used to converge practically any function.

CRITXX

This routine takes an input shape factor (ALAM) and looks up on a curve the critical Reynolds number.

Uses subroutine SRCHX.

See Chapter XVII of Reference 3.

INPUT VARIABLES

NUMB - number of points in velocity profile curve

XS - surface distance

VS - surface velocity

ALENTH - characteristic blade length

TTZERO - total temperature of free stream
PTZERO - total pressure of free stream
UCRIT - sonic velocity of free stream
AF - average specific heat ratio
UIA - free stream velocity
DIA - leading edge diameter
DX - integration interval
PRINT - print interval

OUTPUT VARIABLES

Laminar

X - surface distance
UX - surface velocity
T - static temperature of surface
P - static pressure of surface
VISM - kinematic viscosity
DEL - laminar boundary layer thickness
THETA - momentum loss thickness
DELSTR - boundary layer displacement thickness
UNDVFS - characteristic surface Reynolds number
TRMCRT - critical surface Reynolds number
ALAM - velocity profile shape factor
H - universal function
DELT - thermal boundary layer thickness
HL - convection heat-transfer coefficient
TND - adiabatic wall temperature

Turbulent

X - surface distance
UX - surface velocity
T - static temperature of surface
P - static pressure of surface
VISN - kinematic viscosity
TAP - adiabatic wall temperature
CF2 - surface friction coefficient

THETA - momentum loss thickness
PN - Prandtl number
RHO - density
TUQV - Reynolds number associated with momentum loss thickness
HX - turbulent heat-transfer coefficient

INPUT FORMAT

First Cards

Curve title card (12A6)

Used to identify the particular velocity profile

Second Cards

NUMB (I3)

Number of points in velocity versus surface distance curve

Next NUMB cards

XS VS (2F10.0)

Surface distance and velocity cards

Next Card

Case title card (12A6)

Used to identify the particular case

Next Card(s)

NAMELIST/INPUT/

Case input; see input variables for definition.

```
$IBFTC LUMIT   M94,XR7
      DIMENSION ATITLE(12)
      NAMELIST/INPUT/ALENTH,TTZERO,PTZERO,UCRIT,AK,UIN,DIA,
     AOX,PRINT
      CALL READIN(XMAX)
      READ(5,510)(ATITLE(I),I=1,12)
      WRITE(6,511)(ATITLE(I),I=1,12)
510   FORMAT(12A6)
511   FORMAT(1H1,12A6)
      READ(5,INPUT)
      R=DIA/2.
      AINT=0.0
      BINT=0.0
      VISKI=0.0
      URATI1=0.0
      URATI2=0.0
      X=0.0
      UX5=0.0
      I=0
      IBIN=1
      ALAMO=7.053
C*****************************************************************************
C******************************                     ***************************
C******************************   START OF LAMINAR  ***************************
C******************************                     ***************************
C*****************************************************************************
C
C   X=ZERO CALCULATIONS
C
      DXB=DX
      ALAM=7.0529
      X=0.0
      CALL CURVE(X,DXB,UX,UPX,UPPX)
      T=TTZERO
      P=PTZERO
      CALL PROPER(T,P,AMU,RHO,PN,CP)
      VISK=AMU/RHO
      VISKO=VISK
      CFL=1.328/SQRT(UIN*ALENTH/VISKO)
      DEL=SQRT(ALAM*VISK/UPX)
      THETA=0.11746*DEL
      DELSTR=2.554*THETA
      CALL PRAN(PN,CONST1)
      ANO=2.*CONST1*SQRT(UIN*DIA/VISK)
      DELT=2.*DIA/ANO
      RAT=DEL/DELT
      H=0.3-0.3*RAT+0.13333*(RAT**2.)-0.0214286*(RAT**4.)
     A+0.005555*(RAT**5.)
      HL=2.*CP*AMU/(PN*DELT)*4.6275
      TAD=T
      HO=H
      DELO=DEL
C
C   END OF X=ZERO CALCULATIONS
C
      IPS=PRINT/DX+0X
      UX5S=UX**5.
      WRITE(6,100)X,UX,T
      WRITE(6,101)P,VISK,THETA
      WRITE(6,102)DEL,DELSTR,UDQVIS
      WRITE(6,103)TRMCRT,ALAM,PN
      WRITE(6,104)DELTA,DELT,HL
```

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```
      WRITE(6,105)TAD
100   FORMAT(8HO     X=,E15.7,5X,7H    UX=,E15.7,5X,7H     T=,E15.7)
101   FORMAT(8H      P=,E15.7,5X,7H  VISK=,E15.7,5X,7H THETA=,E15.7)
102   FORMAT(8H    OEL=,E15.7,5X,7HOELSTR=,E15.7,5X,7HUOOVIS=,E15.7)
103   FORMAT(8H TRMCRT=,E15.7,5X,7H  ALAM=,E15.7,5X,7H    PN=,E15.7)
104   FORMAT(8H  DELTA=,E15.7,5X,7H  DELT=,E15.7,5X,7H    HL=,E15.7)
105   FORMAT(8H    TAD=,E15.7)
      IP=0
      UX5=UX**5.
11    I=I+1
      AI=I
      X=AI*OX
      IP=IP+1
14    CALL CURVE(X,DX,UX,UPX,UPPX)
      IF(UX .LT. 6.0) GO TO 11
      UX5=UX**5.
      T=TTZERO*(1.-((AK-1.)/(AK+1.))*(UX/UCRIT)**2.)
      P=PTZERO*((T/TTZERO)**(AK/(AK-1.)))
      CALL PROPER(T,P,AMU,RHO,PN,CP)
      VISK=AMU/RHO
      CALL PRAN(PN,CONST1)
      ANO=2.*CONST1*SQRT(UIN*OIA/VISK)
      OELTO=2.*OIA/ANO
      IH=1
      OELO2=ALAMO*VISK/UPX
      TERM1=DELO2*UX**6./(34.*VISK)
      UEINT1=0.0
      OTUM2=0.0
      OELAS=DELO
      OEL2AS=OELAS*OELAS
      GO TO 2
1     I=I+1
      AI=I
      X=AI*OX
      IP=IP+1
2     CONTINUE
      UX5S=UX5
      UXS=UX
      CALL CURVE(X,OX,UX,UPX,UPPX)
      UX5=UX**5.
      T=TTZERO*(1.-((AK-1.)/(AK+1.))*(UX/UCRIT)**2.)
      P=PTZERO*((T/TTZERO)**(AK/(AK-1.)))
      CALL PROPER(T,P,AMU,RHO,PN,CP)
      VISK=AMU/RHO
      VISKI=VISKI+VISK*DX
      TERM1=TERM1+((UX5+UX5S)/2.)*OX
      C=34.*VISK/((UX5*UX+UX5S*UXS)/2.)
      OEL2A=DEL2AS+C*((UX5+UX5S)/2.)*DX
      OELA=SQRT(DEL2A)
      OEL2E=C*TERM1
      OELE=SQRT(OEL2E)
      OEL=OELE
      OEL2=DEL2E
      THETA=0.11746*OEL
      DELSTR=2.554*THETA
      UOOVIS=UX*DELSTR/VISK
      ALAM=DEL2*UPX/VISK
      CALL CRITCL(ALAM,TRMCRT)
      IF(UDOVIS .GE. TRMCRT) GO TO 190
      GO TO (50,99),IH
C
C   USED FIRST TIME ONLY
```

```
C
50    IH=2
      X1=X
      CALL CURVE(X1,DX,UX1,UPX1,UPPX1)
      Z1=PN*(DELO*UX1*HO)**2./(4.*VISK)
      Z2=Z1+(HO*(UX1+UX)/2.)*DX
      ZZ1=DELO**2.*UX1**6./(34.*VISK)
      ZZ2=ZZ1+((UX1**5.+UX**5.)/2.)*DX
      HD2=0.11765*UX**4.*Z2/(PN*ZZ2)
      CALL OTFRM(HD2,DELTA2)
      HG=HD2/(DELTA2**2.)
      AQB=HD2/((0.11765/PN)*UX**4.)
      CQD=(HD2/((0.11765/PN)*UX**4.))*HG
      TERMC=UX*HG*DX
      TERMD=C/CQD
      TERMB=TERMD
      TERMA=B/AQB
      GO TO 108
C
C   USED ALL BUT FIRST TIME
99    CONTINUE
      TERMA=TERMA+((UX+UXS)/2.)*DX
      TERMB=TERMB+((UX**5.+UXS**5.)/2.)*DX
      D2HG=(0.11765/PN)*UX**4.*TERMA/TERMB
      CALL OTFRM(D2HG,DELTA1)
      HG=D2HG/(DELTA1**2.)
      TERMC=TERMC+((UX+UXS)/2.)*((HG+HS)/2.)*DX
      TERMD=TERMB
      D2HG1=(0.11765/PN)*UX**4.*TERMC/(TERMD*HG)
      CALL OTFRM(D2HG1,DELTA2)
108   H=HG
      DELTA=DELTA2
      DELT=DELTA*DEL
      HL=2.*CP*AMU/(PN*DELT)*4.62725
      TAO=T+(TTZERO-T)*SQRT(PN)
      DXL=DX/ALENTH
      AINT=AINT+(((UX/UIN)**5.+(UXS/UIN)**5.)/2.)*DXL
      C1STR=((CFL/2.)*SQRT(AINT))**1.25
      UXS=UX
      HS=H
      IF(IP .NE. IPS) GO TO 1
500   IP=0
      WRITE(6,100)X,UX,T
      WRITE(6,101)P,VISK,THETA
      WRITE(6,102)DEL,DELSTR,UDQVIS
      WRITE(6,103)TRMCRT,ALAM,PN
      WRITE(6,104)DELTA,DELT,HL
      WRITE(6,105)TAO
      GO TO 1
C*****************************************************************************
C*****************************                          *****************************
C*****************************   END OF LAMINAR   *****************************
C*****************************                          *****************************
C*****************************************************************************
190   WRITE(6,211)X
211   FORMAT(1H2,16HTRANSITION AT X=,E15.7)
      WRITE(6,100)X,UX,T
      WRITE(6,101)P,VISK,THETA
      WRITE(6,102)DEL,DELSTR,UDQVIS
      WRITE(6,103)TRMCRT,ALAM,PN
      WRITE(6,104)DELTA,DELT,HL
      WRITE(6,105)TAO
```

```
      XT=X
      VISKA=VISK1/XT
      C1STRS=C1STR
C ***************************************************************************
C ***************************                          ***************************
C ***************************   START OF TURBULENT   ***************************
C ***************************                          ***************************
C ***************************************************************************
      IF(IP .EQ. IPS) IP=0
800   I=I+1
      AI=I
      UXS=UX
      X=AI*DX
      IP=IP+1
      CALL CURVE(X,DX,UX,UPX,UPPX)
      T=TTZERO*(1.-((AK-1.)/(AK+1.))*(UX/UCRIT)**2.)
      P=PTZERO*((T/TTZERO)**(AK/(AK-1.)))
      CALL PROPER(T,P,AMU,RHO,PN,CP)
      VISK=AMU/RHO
      TAD=T+(TTZERO-T)*(PN**(1./3.))
      BINT=BINT+(((UX/UIN)**3.5+(UXS/UIN)**3.5)/2.)*DXL
      CF2=0.016/((UIN*ALENTH/VISK)**0.25)
      THQL=(UX/UIN)**(-3.)*((C1STRS+CF2*BINT)**0.8)
      THETA=THQL*ALENTH
      TUQV=THETA*UX/VISK
      TAUQDU=0.0128/(TUQV**0.25)
      HX=TAUQDU*RHO*CP*UX*(3600./778.)/
     A(1.+5.*SQRT(TAUQDU )*((PN-1.)+ALOG(1.+(5./6.)*(PN-1.))))
      IF(IP .EQ. IPS) GO TO 900
825   IF(X .LT. XMAX) GO TO 800
1111  STOP
900   IP=0
      WRITE(6,100)X,UX,T
      WRITE(6,101)P,VISK,THETA
      WRITE(6,901)CF2,RHO,TUQV
      WRITE(6,902)PN,TAD,HX
901   FORMAT(8H    CF2=,E15.7,5X,7H   RHO=,E15.7,5X,7H  TUQV=,E15.7)
902   FORMAT(8H     PN=,E15.7,5X,7H   TAD=,E15.7,5X,7H    HX=,E15.7)
      GO TO 825
C ***************************************************************************
C ***************************                          ***************************
C ***************************    END OF TURBULENT     ***************************
C ***************************                          ***************************
C ***************************************************************************
      END
```

```
$IBFTC VLOCT    M94,XR7,DECK
      SUBROUTINE READIN(XMAX)
      DIMENSION XS(200),VS(200)
      DIMENSION ATITLE(12)
      READ(5,510)(ATITLE(I),I=1,12)
      WRITE(6,511)(ATITLE(I),I=1,12)
510   FORMAT(12A6)
511   FORMAT(1H1,12A6)
      READ(5,100)NUMB
      READ(5,101)(XS(I),VS(I),I=1,NUMB)
100   FORMAT(I3)
101   FORMAT(2F10.0)
      DO 1 I=1,NUMB
      I=I
1     XS(I)=XS(I)/12.
      XMAX=XS(I)
      RETURN
      ENTRY CURVE(X,DX,UE,UEP,UEPP)
      X1=X+DX
      X2=X1+DX
      K=0
      NPT=4
      UE=TLOOK(X,XS,VS,NUMB,NPT,K,ILAST)
      UE1=TLOOK(X1,XS,VS,NUMB,NPT,K,ILAST)
      UE2=TLOOK(X2,XS,VS,NUMB,NPT,K,ILAST)
      UEP=((UE1-UE)/(X1-X))
      UEPX=((UE2-UE1)/(X2-X1))
      UEPP=((UEPX-UEP)/(X1-X))
      RETURN
      END
```

```
$IBFTC DTFRMX  M94,XR7,DECK
      SUBROUTINE DTFRM(ANS,DEL)
      DIMENSION Q(9)
      Q(2)=0.0
      Q(3)=0.0
      AJ=50.
      TOL=0.0001
      DIR=1.01
      TRY=1.5
1     TRY2=TRY*TRY
      TERM=0.3*TRY2-0.3*TRY+0.13333-(0.0214286/TRY2)+
     A0.005555/(TRY2*TRY)
      CALL AFQUIR(Q,TRY,TERM,ANS,AJ,TOL,DIR,ANEW,ICON)
      IF(ICON .EQ. 3) GO TO 5
      IF(ICON .EQ. 2) GO TO 10
      TRY=ANEW
      GO TO 1
5     WRITE(6,100)ANS
100   FORMAT(1H0,19HERROR IN DELTA,ANS=,E15.7)
10    DEL=TRY
      RETURN
      END
```

```
$IBFTC PRANX    M94,XR7,DECK
       SUBROUTINE PRAN(P,C)
       DIMENSION PX(9),CX(9)
       DATA (PX(I),I=1,9)/0.6,0.7,0.8,0.9,1.0,1.1,7.,10.,15./
       DATA (CX(I),I=1,9)/0.466,0.495,0.521,0.546,0.570,
      A0.592,1.18,1.34,1.54/
       CALL SRCHX(P,PX(1),9,0,IL,ATERM)
       C=CX(IL)+ATERM*(CX(IL+1)-CX(IL))
       RETURN
       END
```

```
$IBFTC PROPEX  M94,XR7,DECK
      SUBROUTINE PROPER(T,P,AMU,RHO,PN,CP)
      DIMENSION HT5(31),HT6(31)
C   5 TEMPERATURE (INDEPENDENT VARIABLE TABLE)
C     NUMBER OF POINTS 31
      DATA (HT5(K),K=1,31)/450.,540.,630.,720.,810.,900.,990.,1080.,1170
     A.,1260.,1350.,1440.,1530.,1620.,1710.,1800.,1980.,2160.,2340.,2520
     B.,2700.,2880.,3060.,3240.,3420.,3600.,3780.,3960.,4140.,4320.,4620
     C./
C   6 PRANDTLE NUMBER VERSUS TEMPERATURE
C                             (R)
C      INDEPENDENT VECTOR AT (5)
C     LENGTH 31
C     NPR FOR DRY AIR
      DATA (HT6(K),K=1,31)/.722,.708,.697,.689,.683,.68,.68,.68,.682,.68
     A4,.686,.689,.692,.696,.699,.702,.706,.714,.722,.726,.734,.741,.749
     B,.759,.767,.783,.803,.831,.863,.916,.972/
      NP=4
      NT=31
      KL=0
C  T=DEGREES RANKIN
C  P=POUNDS/SQ. IN.
C  AMU=POUNDS*SEC./SQ. FT.
C  RHO=POUNDS*SEC. SQ./FT.**4
C  CP=FT.SQ./(SEC. SQ. DEGREE RANKIN)
C  TK=BTU/(HR FT DEGREE RANKIN)
C  PN=UNITLESS
C  VIS=POUNDS/HR FT
C  T3=DEGREES KELVIN
C  RX=BTU/(POUND DEGREE RANKIN)
C  CPX=BTU/(POUND DEGREE RANKIN)
      CALL PRDCOM(0.0,T,X1,X2,CPX,RX,X3,X4)
      T3=0.555556*T
      VIS=0.00353*T3**1.5/(T3+110.4)
      TK=0.6325*SQRT(T3)*0.00248/(1.+245.4*10.**(-12./T3)/T3)
      PN=TLOOK(T,HT5,HT6,NT,NP,KL,ILAST)
      CP=CPX*32.174049*778.26
      AMU=VIS/(3600.*32.174049)
      RHO=(P*144./(RX*778.26*T))/32.174049
      RETURN
      END
```

```
$IBFTC TLOOKX  M94/2,XR7,DECK
      FUNCTION TLOOK(P,PT,QT,NT,NP,K,ILAST)
C     PT IS TABLE OF INDEPENDENT VARIABLES
C     QT IS TABLE OF DEPENDENT VARIABLES
C     NT = SIZE OF ABOVE TABLES
C     NP = NUMBER OF POINTS FOR INTERPOLATION
C     K = 0, LIMIT OUTPUT TO BOUNDARY OF TABLE
C     K = 1, EXTRAPOLATE FOR VALUES OUTSIDE TABLE
      DIMENSION PT(1), QT(1), XT(10), YT(10)
      IF(ILAST .LE. 0) ILAST = 1
      I = ILAST+1
      IF(PT(1) - PT(NT)) 4,15,15
C     TABLE PT IS IN ASCENDING ORDER
4     IF(PT(I) .GE. P  .AND.  PT(ILAST) .LE. P) GO TO 8
      DO 5 I=1,NT
      IF(P .LE. PT(I)) GO TO 8
5     CONTINUE
      ILAST = NT-1
6     IF(K .GE. 1) GO TO 7
      TLOOK = QT(NT)
      RETURN
7     IL = NT-NP+1
      GO TO 20
8     IF(I .GT. 1) GO TO 10
      ILAST = 1
      IF(K .GE. 1) GO TO 9
      TLOOK = QT(1)
      RETURN
9     IL = 1
      GO TO 20
10    ILAST = I-1
      IL = I-NP/2
      GO TO 20
C     TABLE PT IS IN DESCENDING ORDER
15    IF(PT(I) .LE. P  .AND.  PT(ILAST) .GE. P) GO TO 8
      DO 16 I=1,NT
      IF(P .GE. PT(I)) GO TO 8
16    CONTINUE
      GO TO 6
20    IF(IL .LT. 1) IL = 1
      IF(IL .GT. NT-NP+1) IL = NT-NP+1
      DO 21 J = 1,NP
      L = IL+J-1
      XT(J) = PT(L)
21    YT(J) = QT(L)
      CALL LAGRNG(P,Y,XT,YT,NP)
      TLOOK = Y
      RETURN
      END
```

```
$IBFTC LAGRNG  M94/2,XR7,DECK
      SUBROUTINE LAGRNG(X,Y,XT,YT,N)
C
C     THIS ROUTINE USES A LAGRANGIAN POLYNOMIAL BASED ON N TABULAR
C     POINTS TO INTERPOLATE Y AS A FUNCTION OF X IN A TWO DIMENSIONAL
C     TABLE.
C
      DIMENSION XT(1), YT(1)
      DO 1 I=1,N
      IF(X .EQ. XT(I)) GO TO 5
1     CONTINUE
      L1 = 1
      L2 = N-1
      S = (XT(N)-XT(1))/ABS(XT(N)-XT(1))
6     DO 7 I=L1,L2
      IF(ABS(XT(I)-XT(I+1)) .GT. .001*ABS(XT(I))) GO TO 7
      IF((X-XT(I))*S .LE. 0.) GO TO 8
      L1 = I+1
      GO TO 6
8     L2 = I
      GO TO 9
7     CONTINUE
      L2 = N
9     Y = 0.
      DO 3 I=L1,L2
      Z = 1.
      DO 2 J=L1,L2
      IF(J .EQ. I) GO TO 2
      Z = Z*(X-XT(J))/(XT(I)-XT(J))
2     CONTINUE
3     Y = Y+Z*YT(I)
      RETURN
5     Y = YT(I)
      RETURN
      END
```

```
$IBFTC SRCHXX  M94/2,XR7,DECK
      SUBROUTINE SRCHX(V,VT,N,KEX,IL,C)
C
C     THIS ROUTINE LOCATES V IN TABLE VT
C     IF KEX = 0, LIMIT OUTPUT TO TABLE BOUNDARY
C     IF KEX = 1, EXTRAPOLATE IF V IS OUTSIDE TABLE
      DIMENSION VT(N)
      IF(VT(2) .LT. VT(1)) GO TO 6
C     TABLE VT IS IN ASCENDING ORDER
      DO 1 I=1,N
      IF(V-VT(I)) 2,2,1
1     CONTINUE
15    IL = N-1
      IF(KEX .EQ. 1) GO TO 3
      C = 1.
      RETURN
2     IL = I-1
      IF(I .EQ. 1) GO TO 4
3     C = (V-VT(IL))/(VT(IL+1)-VT(IL))
      RETURN
4     IL = 1
      IF(KEX .EQ. 1) GO TO 3
      C = 0.
      RETURN
C     TABLE VT IS IN DESCENDING ORDER
6     DO 7 I=1,N
      IF(V-VT(I)) 7,2,2
7     CONTINUE
      GO TO 15
      END
```

```
$IBFTC PROCOM  M94,XR7,DECK
      SUBROUTINE PROCOM(FARX,TEX,CSEX,AKEX,CPEX,REX,SEX,HEX)
      IF(TEX-300.)2,3,3
2     WRITE(6,102)
102   FORMAT(1H0,35HPROCOM INPUT TEMPERATURE BELOW 300.)
      RETURN
3     IF(TEX-4500.)5,5,4
4     WRITE(6,103)
103   FORMAT(1H0,36HPROCOM INPUT TEMPERATURE ABOVE 4500.)
      RETURN
5     IF(FARX)6,7,7
6     WRITE(6,104)
104   FORMAT(1H0,38HPROCOM INPUT FUEL-AIR RATIO BELOW ZERO)
      FARX=0.0
C     AIR PATH
7     CPA =((((((1.0115540E-25*TEX-1.4526770E-21)*TEX
     1+7.6215767E-18)*TEX-1.5128259E-14)*TEX-6.7178376E-12)
     2*TEX+6.5519486E-08)*TEX-5.1536879E-05)*TEX+2.5020051E-01
      HEA=(((((((1.2644425E-26*TEX-2.0752522E-22)*TEX
     1+1.2702630E-18)*TEX-3.0256518E-15)*TEX-1.6794594E-12)*TEX
     2+2.1839826E-08)*TEX-2.5768440E-05)*TEX+2.5020051E-01)*TEX
     3-1.7558886E+00
      SEA=+2.5020051E-01*ALOG(TEX)+((((((1.4450767E-26*TEX
     1-2.4211288E-22)*TEX+1.5243153E-18)*TEX-3.7820648E-15)*TEX
     2-2.2392790E-12)*TEX+3.2759743E-08)*TEX-5.1576879E-05)*TEX
     3+4.5432300E-02
      IF(FARX)200,200,8
C     FUEL/AIR PATH
8     IF(FARX-.067623)10,10,9
9     WRITE(6,101)
101   FORMAT(1H0,63HINPUT FUEL-AIR RATIO ABOVE LIMITS, IT HAS BEEN RESET
     2TO 0.067623)
      FARX=0.067623
10    CPF =((((((7.2678710E-25*TEX-1.3335668E-20)*TEX
     1+1.0212913E-16)*TEX-4.2051104E-13)*TEX+9.9686793E-10)*TEX
     2-1.3771901E-06)*TEX+1.2258630E-03)*TEX+7.3816638E-02
      HEF=(((((((9.0848388E-26*TEX-1.9050949E-21)*TEX
     1+1.7021525E-17)*TEX-8.4102208E-14)*TEX+2.4921698E-10)*TEX
     2-4.5906332E-07)*TEX+6.1293150E-04)*TEX+7.3816638E-02)
     3*TEX+3.0581530E+01
      SEF=+7.3816638E-02*ALOG(TEX)+((((((1.0382670E-25*TEX
     1-2.2226118E-21)*TEX+2.0425826E-17)*TEX-1.0512776E-13)*TEX
     2+3.3228928E-10)*TEX-6.8859505E-07)*TEX+1.2258630E-03)*TEX
     3+6.483398E-01
200   CPEX=(CPA+FARX*CPF)/(1.+FARX)
      HEX=(HEA+FARX*HEF)/(1.+FARX)
      SEX=(SEA+FARX*SEF)/(1.+FARX)
      AMW=28.97-.946186*FARX
      REX=1.986375/AMW
      AKEX=CPEX/(CPEX-REX)
      CSEX=SQRT(AKEX*REX*TEX*25031.37)
      RETURN
      END
```

```
$IBFTC AFQUIR  M94,XR7,DECK
      SUBROUTINE AFQUIR(X,AIND,DEPEND,ANS,AJ,TOL,DIR,ANEW,ICON)
      DIMENSION X(9)
C X(1)=NAME OF ARRAY TO USE
C AIND=INDEPENDANT VARIABLE
C DEPEND= DEPENDANT VARIABLE
C ANS=ANSWER UPON WHICH TO CONVERGE
C AJ=MAX NUMBER OF TRYS
C TOL=PERCENT TOLERANCE FOR CONVERGENCE
C DIR=DIRECTION AND PERCENTAGE FOR FIRST GUESS
C ANEW=CALCULATED VALUE OF NEXT TRY AT INDEPENDANT VARIABLE
C ICON=CONTROL   =1 GO THRU LOOP AGAIN
C                =2 YOU HAVE REACHED THE ANSWER
C                =3 COUNTER HAS HIT LIMITS
C X(2)=COUNTER STORAGE
C X(3)=CHOOSES METHOD OF CONVERGENCE
C X(4)=THIRD DEPEND VAR
C X(5)=THIRD IND VAR
C X(6)=SECOND DEPEND VAR
C X(7)=SECOND IND VAR
C X(8)=FIRST DEPEND VAR
C X(9)=FIRST IND VAR
C X(3) MUST BE ZERO UPON FIRST ENTRY TO ROUTINE

      Y=0.
      IF(ANS)1,2,1
1     DEP=DEPEND-ANS
      TOLANS=TOL*ANS
      GO TO 3
2     DEP=DEPEND
      TOLANS=TOL
3     IF(ABS(DEP)-TOLANS)5,5,4
4     IF(X(2)-AJ)8,8,7
5     ANEW=AIND
      X(2)=0.
      ICON=2
      RETURN
6     ANEW=Y
      X(2)=X(2)+1.
      ICON=1
      RETURN
7     ANEW=Y
      X(2)=0.
      ICON=3
      RETURN
8     IF(X(3))9,9,12
C *** FIRST GUESS USING DIR
9     X(3)=1.
      X(8)=DEP
      X(9)=AIND
      IF(AIND)10,11,10
10    Y=DIR*AIND
      GO TO 6
11    Y=DIR
      GO TO 6
12    IF(X(3)-1.)13,13,16
C *** LINEAR GUESS
13    X(3)=2.
      X(6)=DEP
      X(7)=AIND
      IF(X(8)-X(6))14,9,14
14    IF(X(9)-X(7))15,9,15
```

```
15    A=(X(9)-X(7))/(X(8)-X(6))
      Y=X(9)-A*X(8)
      IF(ABS(10.*X(9))-ABS(Y))9,9,6
C *** QUADRATIC GUESS
16    X(4)=DEP
      X(5)=AINO
      IF(X(7)-X(5))18,17,18
17    IF(X(6)-X(4))13,9,13
18    IF(X(6)-X(4))19,13,19
19    IF(X(9)-X(5))23,20,23
20    IF(X(8)-X(4))21,22,21
21    X(9)=X(7)
      X(8)=X(6)
      GO TO 13
22    X(9)=X(7)
      X(8)=X(6)
      X(3)=1.
      IF(X(9))10,11,10
23    IF(X(8)-X(4))24,21,24
24    F=(X(6)-X(4))/(X(7)-X(5))
      A=(X(8)-X(4)-F*(X(9)-X(5)))/((X(9)-X(7))*(X(9)-X(5)))
      B=F-A*(X(5)+X(7))
      C=X(4)+X(5)*(A*X(7)-F)
      IF(A)242,240,242
240   IF(B)241,7,241
241   Y=-C/B
      GO TO 37
242   IF(B)247,243,247
243   IF(C)245,244,245
244   Y=0.
      GO TO 37
245   G=-C/A
      IF(G)7,7,246
246   Y=SQRT(G)
      YY=-SQRT(G)
      GO TO 270
247   IF(C)249,248,249
248   Y=-B/A
      YY=0.
      GO TO 270
249   D=4.*A*C/B**2
      IF(1.-D)13,25,26
25    Y=-B/(2.*A)
      GO TO 37
26    E=SQRT(1.-D)
27    Y=(-B/(2.*A))*(1.+E)
      YY=(-B/(2.*A))*(1.-E)
270   J=4
      DEPMIN=ABS(X(4))
      DO 29 I=6,8,2
      IF(DEPMIN-ABS(X(I)))29,29,28
28    J=I
      DEPMIN=ABS(X(I))
29    CONTINUE
      K=J+1
      IF((X(K)-Y)*(X(K)-YY))32,32,30
30    IF(ABS(X(K)-Y)-ABS(X(K)-YY))37,37,31
31    Y=YY
      GO TO 37
32    IF(J-6)33,34,34
33    JJ=J+2
      KK=K+2
```

```
      GO TO 35
34    JJ=J-2
      KK=K-2
35    SLOPE=(X(KK)-X(K))/(X(JJ)-X(J))
      IF(SLOPE*X(J)*(X(K)-Y))36,36,37
36    Y=YY
37    X(9)=X(7)
      X(8)=X(6)
      X(7)=X(5)
      X(6)=X(4)
      GO TO 6
      END
```

```
$IBFTC CRITXX  M94,XR7,DECK
       SUBROUTINE CRITCL(ALAM,TERM)
       DIMENSION ALMTAB(13),TRMTAB(13)
       DATA(ALMTAB(I),I=1,13)/-6.,-5.,-4.,-3.,-2.,-1.,0.,
      A1.,2.,3.,4.,5.,6./
       DATA(TRMTAB(I),I=1,13)/0.,120.,138.,175.,250.,375.,
      A645.,1125.,2000.,3500.,5500.,8000.,10000./
       CALL SRCHX(ALAM,ALMTAB(1),13,0,IL,C)
       TERM=TRMTAB(IL)+C*(TRMTAB(IL+1)-TRMTAB(IL))
       RETURN
       END
```

```
                        DATA
                         FOR
                   SAMPLE PROBLEM
                         ONE
                  SUCTION SURFACE
050
0.0        0.0
0.0460     979.01
0.0920     1708.05
0.1380     1783.37
0.1840     1872.09
0.2300     1932.82
0.2760     1995.84
0.3220     2040.62
0.3680     2101.52
0.4141     2156.37
0.4601     2244.38
0.5061     2311.80
0.5521     2366.87
0.5981     2422.29
0.6441     2472.06
0.6901     2533.90
0.7361     2611.21
0.7821     2653.90
0.8281     2708.52
0.8741     2789.65
0.9201     2841.08
0.9661     2875.03
1.0121     2926.40
1.0581     2946.46
1.1041     2972.77
1.1501     2987.53
1.1962     2995.23
1.2422     2999.11
1.2882     2998.92
1.3342     2995.76
1.3802     2992.24
1.4262     2980.23
1.4722     2971.30
1.5182     2955.19
1.5642     2932.29
1.6102     2901.40
1.6562     2901.40
1.7022     2882.99
1.7482     2865.65
1.7942     2841.45
1.8402     2822.82
1.8862     2802.41
1.9322     2779.79
1.9783     2762.91
2.0243     2739.22
2.0703     2715.27
2.1163     2692.51
2.1623     2669.67
2.2083     2642.64
2.2543     2646.15
                  SAMPLE PROBLEM NUMBER ONE
 $INPUT ALENTH=0.15945,TTZERO=3510.,PTZERO=57.2,UCRIT=2714.,
 AK=1.26,UIN=900.,DIA=0.013333,PRINT=1.E-2,DX=1.E-5$
```

SUCTION SURFACE

SAMPLE PROBLEM NUMBER ONE

```
      X=  0.                   UX=  0.                   T=  0.3510000E 04
      P=  0.5720000F 02      VISK=  0.9318774E-03    THETA=  0.1893401E-04
    OEL=  0.1611954E-03    OELSTR=  0.4835746E-04   UOOVIS= -0.0000000E-19
 TRMCRT= -0.0000000E-19      ALAM=  0.7052900E 01       PN=  0.7742500E 00
  OELTA= -0.0000000E-19      OELT=  0.2284553E-03       HL=  0.4968198E 03
    TAO=  0.3510000E 04

      X=  0.9990000E-02        UX=  0.1789103E 04        T=  0.3334522E 04
      P=  0.4461234E 02      VISK=  0.1103231E-02    THETA=  0.3177282E-04
    OEL=  0.2704991E-03    OELSTR=  0.8114778E-04   UOOVIS=  0.1315968E 03
 TRMCRT=  0.7859695E 03      ALAM=  0.2936866E-00       PN=  0.7628164E 00
  OELTA=  0.1415952E 01      OELT=  0.3830136E-03       HL=  0.2908361E 03
    TAO=  0.3487783E 04

      X=  0.1998000E-01        UX=  0.1946693E 04        T=  0.3302247E 04
      P=  0.4255835E 02      VISK=  0.1139101E-02    THETA=  0.5320450E-04
    OEL=  0.4529584E-03    OELSTR=  0.1358843E-03   UOOVIS=  0.2322226E 03
 TRMCRT=  0.3637746E 04      ALAM=  0.3068873E 01       PN=  0.7614853E 00
  OELTA=  0.1304691E 01      OELT=  0.5909708E-03       HL=  C.1876126E 03
    TAO=  0.3483539E 04

      X=  0.2997000E-01        UX=  0.2090257E 04        T=  0.3270475E 04
      P=  0.4061036E 02      VISK=  0.1175906E-02    THETA=  0.6427801E-04
    OEL=  0.5472332E-03    OELSTR=  0.1641660E-03   UOOVIS=  0.2918169E 03
 TRMCRT=  0.5844446E 04      ALAM=  0.4137778E 01       PN=  0.7602210E 00
  OELTA=  0.1305334E 01      OELT=  0.7143219E-03       HL=  0.1544796E 03
    TAO=  0.3479318E 04

      X=  0.3996000E-01        UX=  0.2274878E 04        T=  0.3226294E 04
      P=  0.3801994E 02      VISK=  0.1229694E-02    THETA=  0.6808716E-04
    OEL=  0.5796625E-03    OELSTR=  0.1738946E-03   UOOVIS=  0.3216970E 03
 TRMCRT=  0.7683456E 04      ALAM=  0.4873382E 01       PN=  0.7582584E 00
  OELTA=  0.1349648E 01      OELT=  0.7823404E-03       HL=  0.1401398E 03
    TAO=  0.3473340E 04

      X=  0.4995000E-01        UX=  0.2423690E 04        T=  0.3187962E 04
      P=  0.3588031E 02      VISK=  0.1278979E-02    THETA=  0.7368910E-04
    OEL=  0.6273549E-03    OELSTR=  0.1882020E-03   UOOVIS=  0.3566465E 03
 TRMCRT=  0.5445121E 04      ALAM=  0.3972560E 01       PN=  0.7561379E 00
  OELTA=  0.1367097E 01      OELT=  0.8576547E-03       HL=  0.1271730E 03
    TAO=  0.3467994E 04

      X=  0.5994000E-01        UX=  0.2584312E 04        T=  0.3143864E 04
      P=  0.3353821F 02      VISK=  0.1338901E-02    THETA=  0.769C438E-04
    OEL=  0.6547282E-03    OELSTR=  0.1964138E-03   UOOVIS=  0.3791129E 03
 TRMCRT=  0.1000000E 05      ALAM=  0.6485039F 01       PN=  0.7536534E 00
  OELT4=  0.1396174E 01      OELT=  0.9141145E-03       HL=  0.1185997E 03
    TAO=  0.3461718E 04

      X=  0.6993000E-01        UX=  0.2727728E 04        T=  0.3102099E 04
      P=  0.3143352E 02      VISK=  0.1399058E-02    THETA=  0.8105530E-04
    OEL=  0.6900672E-03    OELSTR=  0.2070152E-03   UOOVIS=  0.4036154E 03
 TRMCRT=  0.1000000E 05      ALAM=  0.7281691E 01       PN=  0.7513070E 00
  OELTA=  0.1412590E 01      OELT=  0.9747819E-03       HL=  0.1105676E 03
    TAO=  0.3455659E 04

      X=  0.7992000E-01        UX=  0.2869559E 04        T=  0.3058578E 04
      P=  0.2935326E 02      VISK=  0.1465535E-02    THETA=  0.8512876E-04
    OEL=  0.7247468E-03    OELSTR=  0.2174188E-03   UOOVIS=  0.4257123E 03
 TRMCRT=  0.3966627E 04      ALAM=  0.3233314E 01       PN=  0.7489302E 00
```

OELTA=	0.1426261E 01	DELT=	0.1033678E-D2	HL=	D.1D36D72E D3
TAD=	0.3449242E 04				

X=	0.899100DE-D1	UX=	D.2958661E D4	T=	D.3030109E 04
P=	0.28D5268E D2	VISK=	0.1511253E-D2	THETA=	D.92046D1E-04
OEL=	0.7836371E-D3	DELSTR=	0.2350855E-03	UOQVIS=	D.4602395E D3
TRMCRT=	0.3313718E D4	ALAM=	0.2875812E D1	PN=	D.7475599E DD
DELTA=	0.1415977E D1	DELT=	0.11D9612E-D2	HL=	D.9608484E D2
TAO=	0.3445D30E D4				

X=	0.999D000E-01	UX=	D.2995553E D4	T=	D.3018D67E 04
P=	0.2751652E D2	VISK=	D.1531149E-02	THETA=	0.1D15453E-03
DEL=	0.8645D95E-D3	DELSTR=	0.2593467E-D3	UDQVIS=	D.5D73881E D3
TRMCRT=	0.9882192E 03	ALAM=	.715040DE 00	PN=	D.7469943E DD
OELTA=	0.1388053E 01	DELT=	0.1199985E-D2	HL=	D.8867655E D2
TAD=	0.3443239E 04				

TRANSITION AT X= 0.1D7670DE-DD

X=	0.107670DE-0D	UX=	D.2998734E 04	T=	0.3017D21E D4
P=	0.2747D37E D2	VISK=	D.1532892E-D2	THETA=	D.11D09D2E-D3
DEL=	0.9372568E-03	DELSTR=	D.28117D3E-D3	UDQVIS=	D.55D0421E D3
TRMCRT=	D.5496133E 03	ALAM=	-D.3532841E-DD	PN=	D.7469456E 00
OELTA=	D.1361217E D1	DELT=	D.1275678E-D2	HL=	D.834D075E D2
TAD=	0.3443D83E D4				

X=	0.109890DE-0D	UX=	D.2996996E 04	T=	0.3D17592E D4
P=	0.2749557E D2	VISK=	D.1531939E-D2	THETA=	D.9122335E-D4
CF2=	0.9145630E-03	RHD=	0.7642255E-D3	TUQV=	D.178464DE D3
PN=	0.7469722E 00	TAO=	D.3464371E D4	HX=	D.3184159E D3

X=	0.11988D0E-0D	UX=	0.2977954E 04	T=	D.3D2383DE D4
P=	0.27772D9E D2	VISK=	D.1521585E-D2	THETA=	D.1268618E-D3
CF2=	0.9130137E-D3	RHD=	0.77D319DE-D3	TUQV=	D.2482862E D3
PN=	D.7472640E DD	TAD=	D.3465DD7E D4	HX=	D.2916595E D3

X=	0.129870DE-0D	UX=	0.293557DE 04	T=	D.3D3757DE D4
P=	D.2838903E D2	VISK=	D.1499D94E-D2	THETA=	D.1642179E-D3
CF2=	0.9D96209E-03	RHO=	D.7838692E-D3	TUQV=	D.3215763E D3
PN=	D.7479144E OD	TAD=	D.34664D3E D4	HX=	D.2728721E D3

X=	0.1398600E-00	UX=	0.2893645E 04	T=	D.3D50968E D4
P=	0.29001D3E D2	VISK=	0.1477577E-D2	THETA=	0.2009674E-03
CF2=	0.9063392E-03	RHO=	0.79725D9E-D3	TUQV=	D.3935687E D3
PN=	0.7485592E 00	TAD=	D.3467759E 04	HX=	D.2591173E D3

X=	0.14985D0E-0D	UX=	D.2839714E 04	T=	D.3D67919E D4
P=	0.2979026E D2	VISK=	D.145D926E-D2	THETA=	0.241D173E-03

CF2=	0.9022244E-03	RHO=	0.8144224E-03	TUQV=	0.4717127E 03
PN=	0.7494271E 00	TAD=	0.3469474E 04	HX=	0.2474587E 03
X=	0.1598400E-00	UX=	0.2786490E 04	T=	0.3084336E 04
P=	0.3057077E 02	VISK=	0.1425708E-02	THETA=	0.2821632E-03
CF2=	0.8982782E-03	RHO=	0.8313121E-03	TUQV=	0.5514767E 03
PN=	0.7503235E 00	TAD=	0.3471133E 04	HX=	0.2377090E 03
X=	0.1698300E-00	UX=	0.2732069E 04	T=	0.3100800E 04
P=	0.3136976E 02	VISK=	0.1400985E-02	THETA=	0.3253351E-03
CF2=	0.8943584E-03	RHO=	0.8485095E-03	TUQV=	0.6344379E 03
PN=	0.7512347E 00	TAD=	0.3472787E 04	HX=	0.2291490E 03
X=	0.1798200E-00	UX=	0.2672002E 04	T=	0.3118595E 04
P=	0.3225190E 02	VISK=	0.1374886E-02	THETA=	0.3726592E-03
CF2=	0.8901637E-03	RHO=	0.8673923E-03	TUQV=	0.7242392E 03
PN=	0.7522297E 00	TAD=	0.3474562E 04	HX=	0.2211537E 03

DATA
FOR
SAMPLE PROBLEM
TWO
PRESSURE SURFACE

```
052
0.0       0.0
0.020     450.
0.0398    858.41
0.060     1220.
0.0795    1509.01
0.1193    619.57
0.1591    597.11
0.1988    597.11
0.2386    594.67
0.2784    597.11
0.3182    597.11
0.3579    597.11
0.3977    602.20
0.4675    608.53
0.4772    624.25
0.5170    627.84
0.5568    638.86
0.5965    657.37
0.6363    680.57
0.6761    703.61
0.7158    722.00
0.7556    758.18
0.7954    776.07
0.8352    818.28
0.8749    836.17
0.9147    876.76
0.9545    896.55
0.9942    926.74
1.0340    944.86
1.0738    972.54
1.1135    997.11
1.1533    1027.38
1.1931    1050.58
1.2328    1094.16
1.2726    1146.04
1.3124    1269.38
1.3522    1319.13
1.3919    1348.27
1.4317    1400.73
1.4715    1442.27
1.5112    1492.66
1.5510    1539.72
1.5908    1577.51
1.6305    1645.02
1.6703    1731.88
1.7101    1809.32
1.7498    1911.27
1.7896    1981.68
1.8294    2089.07
1.8692    2189.85
1.9089    2280.51
1.9487    2382.70
```

SAMPLE PROBLEM NUMBER TWO

```
$INPUT ALENTH=0.15945,TTZERO=3510.,PTZERO=57.2,UCRIT=2714.,
AK=1.26,UIN=900.,DIA=0.013333,PRINT=1.E-2,DX=1.E-5$
```

PRESSURE SURFACE

SAMPLE PROBLEM NUMBER TWO

```
     X=  0.
     P=  0.5720000E 02       UX=  0.
   DEL=  0.1537866E-03     VISK=  0.9318774E-03         T=  0.3510000E 04
TRMCRT= -0.0000000E-19   DELSTR=  0.4613487E-04     THETA=  0.1806377E-04
 DELTA= -0.0000000E-19     ALAM=  0.7052900E 01    UOOVIS= -0.0000000E-19
   TAD=  0.3510000E 04     DELT=  0.2284553E-03        PN=  0.7742500E 00
                                                       HL=  0.4968198E 03
```

```
TRANSITION AT X=  0.6940000E-02

     X=  0.6940000E-02
     P=  0.4830857E 02       UX=  0.1481076E 04
   OEL=  0.2126069E-03     VISK=  0.1045191E-02         T=  0.3389744E 04
TRMCRT=  0.7968158E 02   OELSTR=  0.6378055E-04     THETA=  0.2497281E-04
 OELTA=  0.1497112E 01     ALAM= -0.5335987E 0[illegible]    UOOVIS=  0.9037951E 02
   TAD=  0.3494925E 04     OELT=  0.3167091E-03        PN=  0.7653682E 00
                                                       HL=  0.3543541E 03

     X=  0.9990000E-02
     P=  0.5558060E 02       UX=  0.6150699E 03
   CF2=  0.8116362E-03     VISK=  0.9502386E-03         T=  0.3489260E 04
    PN=  0.7724281E 00      RHO=  0.1336008E-02     THETA=  0.4114564E-03
                            TAO=  0.3508290E 04      TUQV=  0.2663273E 03
                                                       HX=  0.1023814E 03

     X=  0.1998000E-01
     P=  0.5568493E 02       UX=  0.5947076E 03
   CF2=  0.8113777E-03     VISK=  0.9490288E-03         T=  0.3490611E 04
    PN   0.7725442E 00      RHO=  0.1337998E-02     THETA=  0.4848506E-03
                            TAD=  0.3508402E 04      TUQV=  0.3038310E 03
                                                       HX=  0.9570405E 02

     X=  0.2997000E-01
     P=  0.5567203E 02       UX=  0.5972618E 03
   CF2=  0.8114096E-03     VISK=  0.9491782E-03         T=  0.3490444E 04
    PN=  0.7725298E 00      RHO=  0.1337752E-02     THETA=  0.5090107E-03
                            TAO=  0.3508388E 04      TUQV=  0.3202904E 03
                                                       HX=  0.9475287E 02

     X=  0.3996000E-01
     P=  0.5551920E 02       UX=  0.6267583E 03
   CF2=  0.8117885E-03     VISK=  0.9509524E-03         T=  0.3488465E 04
    PN=  0.7723598E 00      RHO=  0.1334837E-02     THETA=  0.4668246E-03
                            TAO=  0.3508223E 04      TUQV=  0.3076770E 03
                                                       HX=  0.1002918E 03

     X=  0.4995000E-01
     P=  0.5534436E 02       UX=  0.6589614E 03
                           VISK=  0.9529923E-03         T=  0.3486195E 04
                                                    THETA=  0.4294948E-03
```

CF2=	0.8122236E-03	RHO=	0.1331499E-02	TUQV=	0.2969809E 03
PN=	0.7721659E 00	TAD=	0.3508034E 04	HX=	0.1061871E 03
X=	0.5994000E-01	UX=	0.7249753E 03	T=	0.3481186E 04
P=	0.5496010E 02	VISK=	0.9575137E-03	THETA=	0.3500712E-03
CF2=	0.8131852E-03	RHO=	0.1324157E-02	TUQV=	0.2650542E 03
PN=	0.7717417E 00	TAO=	0.3507616E 04	HX=	0.1197856E 03
X=	0.6993000E-01	UX=	0.8203803E 03	T=	0.3473104E 04
P=	0.5434445E 02	VISK=	0.9648691E-03	THETA=	0.2687294E-03
CF2=	0.8147424E-03	RHO=	0.1312371E-02	TUQV=	0.2284873E 03
PN=	0.7710679E 00	TAD=	0.3506937E 04	HX=	0.1398232E 03
X=	0.7992000E-01	UX=	0.8998981E 03	T=	0.3465604E 04
P=	0.5377816E 02	VISK=	0.9717594E-03	THETA=	0.2327934E-03
CF2=	0.8161931E-03	RHO=	0.1301506E-02	TUQV=	0.2155784E 03
PN=	0.7704551E 00	TAO=	0.3506304E 04	HX=	0.1545282E 03
X=	0.8991000E-01	UX=	0.9756962E 03	T=	0.3457811E 04
P=	0.5319458E 02	VISK=	0.9789883E-03	THETA=	0.2126662E-03
CF2=	0.8171068E-03	RHO=	0.1290285E-02	TUQV=	0.2119511E 03
PN=	0.7698310E 00	TAD=	0.3505642E 04	HX=	0.1668912E 03
X=	0.9990000E-01	UX=	0.1055869E 04	T=	0.3448882E 04
P=	0.5253218E 02	VISK=	0.9873564E-03	THETA=	0.1979046E-03
CF2=	0.8194486E-03	RHO=	0.1277516E-02	TUQV=	0.2116372E 03
PN=	0.7691326E 00	TAO=	0.3504880E 04	HX=	0.1789277E 03
X=	0.1098900E-00	UX=	0.1280759E 04	T=	0.3420074E 04
P=	0.5043962E 02	VISK=	0.1014995E-02	THETA=	0.1360377E-03
CF2=	0.8251241E-03	RHO=	0.1236960E-02	TUQV=	0.1716574E 03
PN=	0.7670051E 00	TAD=	0.3502390E 04	HX=	0.2224568E 03
X=	0.1198800E-00	UX=	0.1408113E 04	T=	0.3401300E 04
P=	0.4911196E 02	VISK=	0.1033550E-02	THETA=	0.1331502E-03
CF2=	0.8288693E-03	RHO=	0.1211049E-02	TUQV=	0.1814045E 03
PN=	0.7659678E 00	TAO=	0.3500756E 04	HX=	0.2359600E 03
X=	0.1298700E-00	UX=	0.1546309F 04	T=	0.3378917E 04
P=	0.4756542E 02	VISK=	0.1056252E-02	THETA=	0.1311976E-03
CF2=	0.8333838E-03	RHO=	0.1180682E-02	TUQV=	0.1920679E 03
PN=	0.7648301E 00	TAO=	0.3498794E 04	HX=	0.2487954E 03
X=	0.1398600E-00	UX=	0.1747139E 04	T=	0.3342657E 04
P=	0.4514228E 02	VISK=	0.1094422E-02	THETA=	0.1196315E-03
CF2=	0.8408131E-03	RHO=	0.1132690E-02	TUQV=	0.1909801E 03
PN=	0.7631662E 00	TAO=	0.3495583E 04	HX=	0.2701050E 03
X=	0.1498500E-00	UX=	0.2003249E 04	T=	0.3290000E 04
P=	0.4179890E 02	VISK=	0.1153108E-02	THETA=	0.1087852E-03
CF2=	0.8518649E-03	RHO=	0.1065585E-02	TUQV=	0.1889882E 03
PN=	0.7609956E 00	TAD=	0.3490855E 04	HX=	0.2921286E 03
X=	0.1598400E-00	UX=	0.2302305E 04	T=	0.3219412E 04
P=	0.3762851E 02	VISK=	0.1238359E-02	THETA=	0.1014762E-03
CF2=	0.8671912E-03	RHO=	0.9803017E-03	TUQV=	0.1886604E 03
PN=	0.7578822E 00	TAD=	0.3484350E 04	HX=	0.3089611E 03

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